Vulnerability of Electric Power Systems to Volcanic Ashfall Hazards

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220 kV transmission lines running adjacent to Tongariro Volcano, two days after the 6 August 2012 Te Māri crater eruption.

ABSTRACT

Volcanic eruptions are powerful natural events which impact strongly on society. As human populations grow and expand into volcanically active areas, their exposure and vulnerability to volcanic hazards is also increasing. Of all volcanic hazards, ashfall is the most likely to impact lifelines because of the large areas affected. The widespread dispersal of ash can cause large-scale disruption of vital infrastructure services, aviation, and primary production. Electric power supply is arguably the most crucial of modern infrastructure systems, especially considering the dependence of other sectors on electricity to maintain functionality.

During and immediately after ashfalls, electric power systems are vulnerable to a number of impacts, but disruption from volcanic ash-induced insulator flashover (unintended, disruptive electrical discharge) is most common. This thesis investigates the vulnerability of electric power systems to volcanic ashfall by examining impacts to the different sectors of the modern power system and exploring appropriate mitigation strategies. Analogue laboratory trials using a pseudo (synthetic) ash are undertaken to verify the environmental, volcanological and electrical parameters that most affect electrical conductivity and therefore the flashover mechanism in these experiments. While dry ash is highly resistant to the flow of electric current, increasing moisture content, soluble salt load, and compaction (bulk density) will reduce this resistance and, in turn, increase the potential for flashover.

Volcanic ash is an acute form of airborne pollution for areas downwind of active volcanoes. Results from laboratory experiments in this thesis suggest that insulator pollution (volcanic ash) performance (dielectric strength) is primarily dictated by (1) the conductivity of the ash, and (2) insulator material, profile (shape) and dimensioning. Composite polymer insulators tested herein effectively minimise sinusoidal leakage current and partial discharge activity and also exhibit higher pollution performance when compared to ceramic equivalents. Irrespective of insulator material,

however, the likelihood of flashover increases significantly once the bottom surface of suspension insulator watersheds become contaminated in wet ash.

The thesis investigates the vulnerability (hazard intensity/damage ratio) of electric power systems to volcanic ashfall hazards. Identification, analysis, and reduction of the risk of ashfall impacts to power networks is explored as a part of holistic volcanic risk assessment. The findings of the thesis contribute to the readiness, response and recovery protocols for large electric power systems in volcanic disasters; which directly affects the functional operation and economics of industrial and commercial society.

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CO-AUTHORSHIP STATEMENT

This thesis comprises five complementary manuscripts published or prepared for publication in international scientific and/or engineering journals. Appendices 1 and 2 are published co-authored, peer reviewed scientific reports. Co-authorship forms are provided before the start of each of the chapters containing published content.

A version of Chapter 2 has been published in ***Bulletin of Volcanology*** (Vol. 74, No. 10, pp. 2221-2241). Mr. Wardman is the first author, and co-authors are Dr. Thomas Wilson, Prof. Jim Cole, Prof. Pat Bodger, and Dr. Carol Stewart. Mr. Wardman wrote the majority of the manuscript. Dr. Thomas Wilson contributed significantly to its refinement while co-authors Prof. Pat Bodger, Prof. Jim Cole and Dr. Carol Stewart offered insightful discussion and review.

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A version of Chapter 4 has been published in ***IEEE Transactions on Dielectrics and Electrical Insulation*** (Vol. 20, No. 2, pp. 414-420). Mr. Wardman is the first author, accompanied by Dr. Thomas Wilson, and Prof. Pat Bodger as co-authors. Mr. Wardman conceived the manuscript, developed laboratory trials, conducted laboratory analysis, interpreted results and wrote the manuscript. Dr. Thomas Wilson and Prof. Pat Bodger provided in-depth discussion and review of the manuscript.

Chapter 5 is intended for submission. Mr. Wardman is first author, and Dr. Stewart Hardie, Dr. Thomas Wilson and Prof. Pat Bodger are co-authors. The manuscript was conceived through discussions between Mr. Wardman and Dr. Thomas Wilson and Prof. Pat Bodger. Mr. Wardman developed laboratory trials, conducted laboratory analysis, interpreted results and wrote the manuscript. All co-authors provided in-depth review and discussion of the manuscript.

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LIST OF ACRONYMS

AC	Alternating Current
BET	Bayesian Event Tree
BPA	Bonneville Power Administration
CELEC EP	La Empresa Publica Estrategica Corporacion Electrica Del Ecuador (*English translation*: Strategic Public Enterprise Electric Corporation Ecuador)
CIGRE	Conseil International des Grands Réseaux Électriques (*English translation*: International Council on Large Electric Systems)
DC	Direct Current
DDG	Dust Deposit Gauge
EHV	Extra High Voltage
ELCOM	Papua New Guinea Electricity Commission
ESDD	Equivalent Salt Deposit Density
EEGSA	Empresa Electrica de Guatemala (*English translation*: Electric Company of Guatemala)
HEP	Hydro Electric Power
HV	High Voltage
HVA	Heating, Venting and Air-conditioning
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IC PMS	Inductively Coupled Plasma Mass Spectrometry
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
KEPC	Kyūshū Electric Power Company
LC	Leakage Current

MUL	Montserrat Utilities Ltd.
NGK	Nippon Gaishi Kaisha (*English translation*: Japan Insulator Company)
NERC	North American Electric Reliability Corporation
NSDD	Non-soluble Deposit Density
PD	Partial Discharge
RCL meter	Instrument used to measure Resistance (R), Capacitance (C), and Inductance (L)
rms	root mean square
RTV	Room Temperature Vulcanising
SPS	Site Pollution Severity
USGS	United States Geological Survey
UC	University of Canterbury (New Zealand)
UV	Ultraviolet
VEI	Volcanic Explosivity Index
V_{min}	Minimum flashover voltage
V_{50}	50% flashover voltage
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

Chapter 1

Introduction

Volcanic eruptions are spectacular displays of Nature's raw and irrepressible power. An explosive event the size of the Toba eruption, Indonesia, ca. 74 ka, is perhaps the only kind of natural hazard other than the impact from a large near earth object (e.g. an asteroid) capable of causing global catastrophe (McGuire, 2006). Comparatively small eruptions, however, can still cause widespread disruption, damage and economic and human loss. The 1902 eruption of Mont Pelée on the French Caribbean island of Martinique is a good example, where a moderate-sized eruption produced a flow of hot ash and gases, killing all but two of the capital's 29,000 inhabitants (Boudan and Gourgaud, 1989; Witham, 2005). As an estimated 9% of the world's population lives within 100 km of a historically active volcano (Horwell and Baxter, 2006), increasing global population, exponential growth of megacities close to active volcanoes, and stresses related to rapid environmental change and globalisation, all contribute to the potential for larger and more serious volcanic crises and disasters than humans have witnessed in the past (Sparks and Aspinall, 2004).

The 18 May 1980 eruption of Mount St Helens, USA was one of the best-documented volcanic events of the 20th century. The deaths of 57 people and in excess of US$1 billion in damage highlighted the effects of volcanic eruptions on human health, critical infrastructure and primary industry (Johnston, 1997). Bonneville Power Administration (BPA), who generates and transmits bulk electrical energy across the Pacific Northwest, endured numerous impacts to their high voltage (HV) transmission system in the weeks following the eruption. Within 10 days of the initial May 18 event, BPA experienced 50 ash-related faults on the system, resulting in a total of 7h 40m in unintended outage time (Nellis and Hendrix, 1980). Of these impacts, insulator flashovers (disruptive discharges) were most common.

Before and during the eruption, there was a complete lack of knowledge on the effects of ashfall on power system apparatus and much anxiety about potential impacts (Johnston, 1997).

Current understanding of ash impacts to electrical infrastructure is limited to subjective information collected from volcanic impact reconnaissance trips (e.g. Leonard et al., 2005; Wilson et al., 2012) and/or investigations carried out by power utility companies in the wake of a volcanic eruption (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995). Most of the information from historical accounts is anecdotal and refers to which element failed, but details of specific damage, reason, length of supply outage and corrective measures taken are often limited. Information about what changes utility providers make to internal systems such as maintenance regimes, asset management, response planning and communication processes as the result of the impact of ash on the network, are largely unknown.

Low probability, but high impact, volcanic eruptions have traditionally been considered insignificant or beyond the scope of power system risk management strategies and practises (Wilson et al., 2009). System operator response to volcanic eruptions have been largely reactive, and not enough has been done to support research to identify areas at risk, assess this risk, and strengthen resilience in the power system.

1.1 VOLCANIC ERUPTIONS

Volcanic eruptions can be broadly divided into two types: effusive, which produce lava flows and explosive, which yield fragmented material (pyroclasts). Volcanic ash can be generated by a plethora of different processes (Dingwell et al., 2011) but most efficiently by explosive eruptions. The most common ash-generating eruption processes are (after Heiken and Wohletz, 1985):

1) *Magmatic*: Decompression of rising magma, gas bubble growth and fragmentation of the foamy magma in the volcanic vent;

2) *Hydrovolcanic*: Explosive mixing of magma with ground surface water;

3) *Phreatic*: Fragmentation of the country rock during rapid expansion of steam and or hot water.

Most volcanoes provide some geophysical or geochemical warning of unrest, however, despite decades of research, it remains very difficult to forecast the beginning, duration or magnitude of an eruption, if at all (Tilling, 1995). Volcanic eruptions may last for seconds or decades, and will vary in intensity with each eruption. The violence of the eruption is primarily controlled by the viscosity of the magma, which is a function of silica content, crystalinity, temperature and the content of H_2O and other volatile species (Heiken and Wohletz, 1985). Volcanic ash particles are incorporated into a gas-rich eruption column that may buoyantly rise up to 50 km into the stratospheric levels of the Earth's atmosphere (Sparks, 1986). Based on these and other eruption parameters such as volume of tephra and eruption duration, the Volcanic Explosivity Index (VEI) is a widely used classification scheme for volcanic eruptions, ranging from VEI 0–8, with VEI 0 the least explosive (Table 1.1). This index is based on both magnitude (erupted volume) and intensity (eruption column height) information and can be applied both to modern and ancient explosive eruptions. The scale is logarithmic, where each successive integer on the scale represents a tenfold increase in observed ejecta criteria, with the exception of between VEI 0 and VEI 1, and VEI 1 and VEI 2 (Newhall and Self, 1982). In general, larger VEI eruptions generate more ash, and therefore present the greatest hazard to regions with high population densities, developed infrastructure and primary industry.

1.2 ASHFALL

Although pyroclastic flows and surges, sector collapses, lahars and ballistic blocks are the most destructive and dangerous of eruption products (Baxter, 1990), ashfall is by far the most widely distributed, and the most likely to be encountered by the public (Blong, 1996). The fallout of ash is controlled by wind strength and direction, environmental conditions, grain size and the height to which the ash reaches (a function of eruption magnitude). In general, the size distribution of ashfall changes as the plume travels away from the vent; with coarser particles falling closer to the vent and finer ash particles carried the greatest distances (e.g. hundreds to thousands of kilometres from the volcano).

Tephra is a general term for volcanic ejecta, and is comprised of pulverised fragments of rock, minerals and volcanic glass. These fragments are classified by size into ash (particles <2 mm) (Figure 1.1), lapilli (2-64 mm) and blocks and bombs (>64 mm) (Sparks et al., 1997). Coarse-grained ash is defined as that with a mean diameter between 0.06 – 2 mm, whilst fine-grained ash has a mean diameter <0.06 mm (Schmid, 1981). However, the nomenclature is adapted throughout this thesis to diversify the terminology.

Previous studies suggest that volcanic ash is the most problematic size fraction for electrical and other critical infrastructure (e.g. Wilson et al., 2009; Wilson et al., 2012). Thus, volcanic ash is the focus of this thesis and is discussed from this stage forward. The types of minerals present in volcanic ash are dependent on the chemistry of the magma from which it was erupted, with the most explosive ash dispersing eruptions of high silica rhyolite (Heiken and Wohletz, 1985). Volcanic ash is hard (~5 on the Mohs hardness scale) and often highly angular. This angularity, together with its hardness, makes ash very abrasive.

Table 1.1: Volcanic explosivity index (adapted from Newhall and Self, 1982).

Volcanic Explosivity Index	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volume of Tephra (m^3)	$<10^4$	10^4-10^6	10^6-10^7	10^7-10^8	10^8-10^9	10^9-10^{10}	10^{10}-10^{11}	10^{11}-10^{12}	$>10^{12}$
Classification	Hawaiian		Strombolian	Vulcanian	Plinian		Katmaian		
Usual Composition	Basaltic			Andesitic		Rhyolitic			
Cloud Column Height (km)	<0.1	0.1-1	1-5	3-15	10-25	>25			
Typical Duration (hrs)		<1	1-6		6-12		>12		
Percentage with Fatalities	1	2	3	12	31	38	60	100	

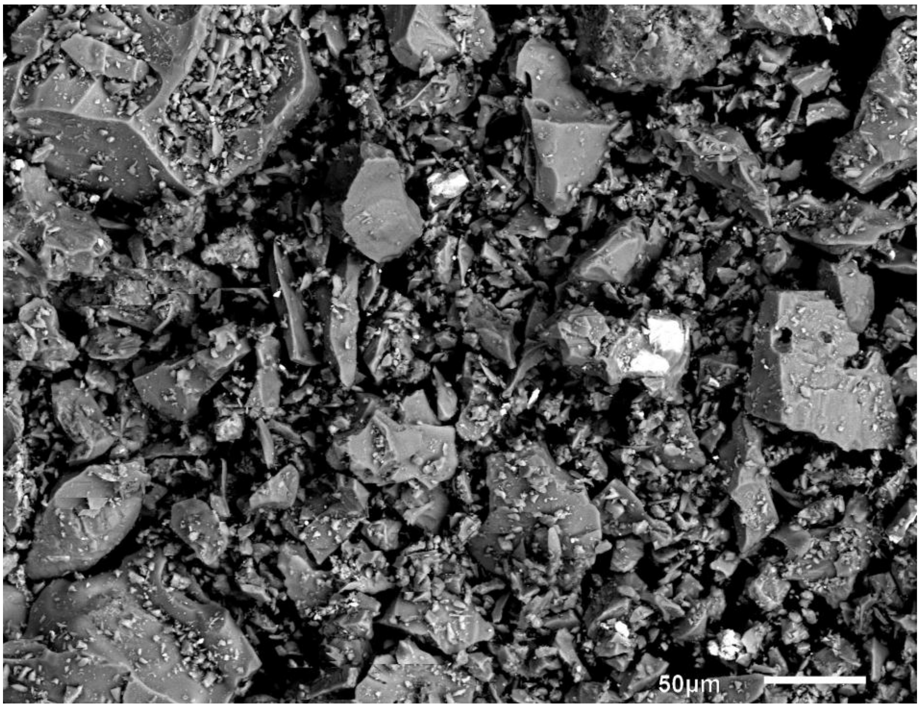

Figure 1.1: Ash particles from the 2009 Redoubt eruption (Alaska, USA).
Image courtesy of Kristi Wallace (USGS/Alaska Volcano Observatory).

During explosive eruptions, volatile gases, aerosols and metals adhere to ash particles during interaction within the volcanic plume (Rose, 1977; Óskarsson, 1980; Smith et al., 1982; Witham et al., 2005) (Figure 1.2). Sulphur and halogen gases and associated anions and cations are adsorbed onto ash surfaces and dry to become soluble salts. Recent studies propose that the formation of soluble halide and sulphate salts is primarily due to the acid-mediated dissolution of the ash's silicate glass and minerals and subsequent precipitation at the ash–liquid interface (Delmelle et al., 2007). This process leads to the formation of thin deposits of salts on the ash's surface. While dry volcanic ash is non-conducting (Nellis and Hendrix, 1980), the fine-grained nature of ash makes it a good retainer of moisture. Once attached soluble salts are dissolved into solution, the ash thus becomes conductive, making it a hazard to power systems.

Newhall & Hoblitt (2002) propose that the probability of volcanic ash generation from any eruption is 92%; 90% for small magnitude eruptions (VEI 0-3) and 100% for large magnitude eruptions (VEI 4-7). The composition of volcanic ash and attached soluble volatiles differ between volcanoes, between eruptions at the same volcano and even between different phases of the same eruption episode. The grain size and thickness of eruptive deposits may also be highly variable, between different eruptions and within the same eruptive episode. Secondary remobilisation and deposition of unconsolidated volcanic products may increase the duration of an eruption's impact for decades afterwards (Wilson et al., 2011). Extensive, above-ground, corridor systems of electrical apparatus used in power generation, transformation, transmission and distribution are often spread out over hundreds of thousands of square kilometres. Thus, ashfall is the most likely volcanic hazard to impact power networks.

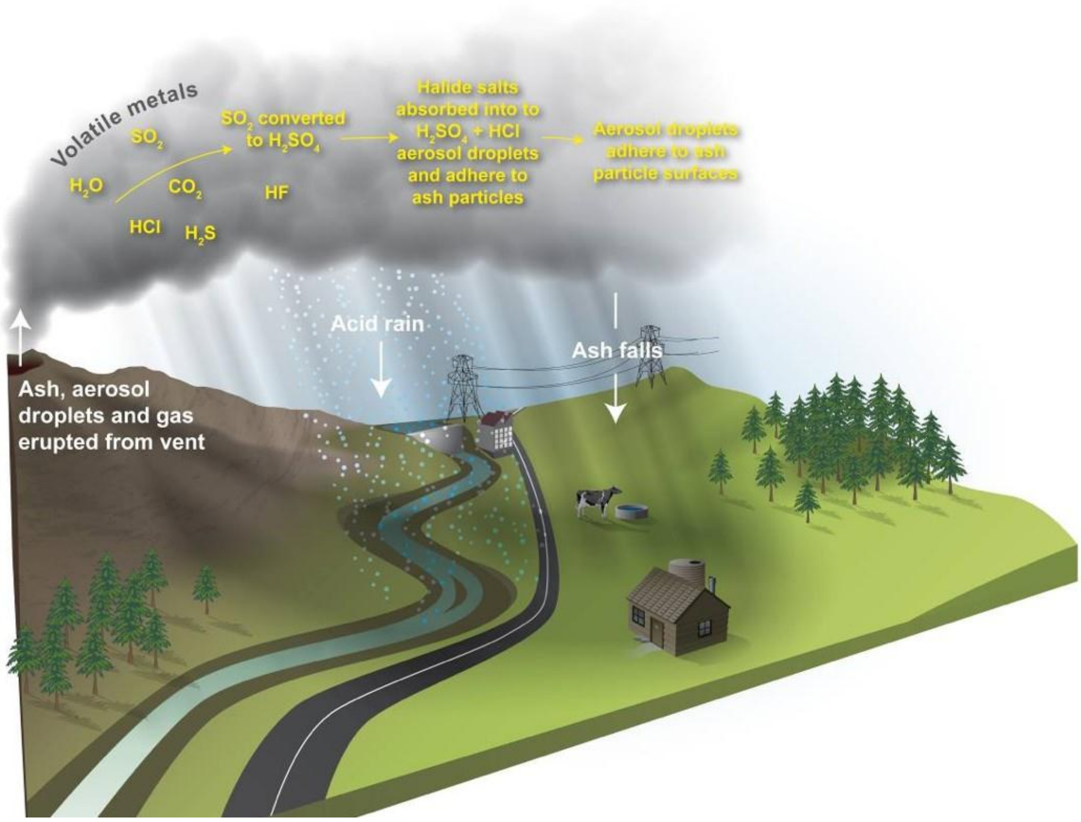

Figure 1.2: Ash particles adsorb volatile gases, aerosols and metals onto their surfaces. These dry to become soluble surface salts and render volcanic ash conductive once dissolved into solution by mist, fog, light rain, etc. (from Wilson et al., 2012).

1.3 VOLCANIC HAZARDS FROM A RISK MANAGEMENT PERSPECTIVE

Volcanic hazards and their consequences (impacts) are best viewed in a risk management framework, where risk identification, risk analysis, risk evaluation, and risk reduction are fundamental steps in the process (Blong, 2000; AS/NZS ISO-31000, 2009) (Figure 1.3).

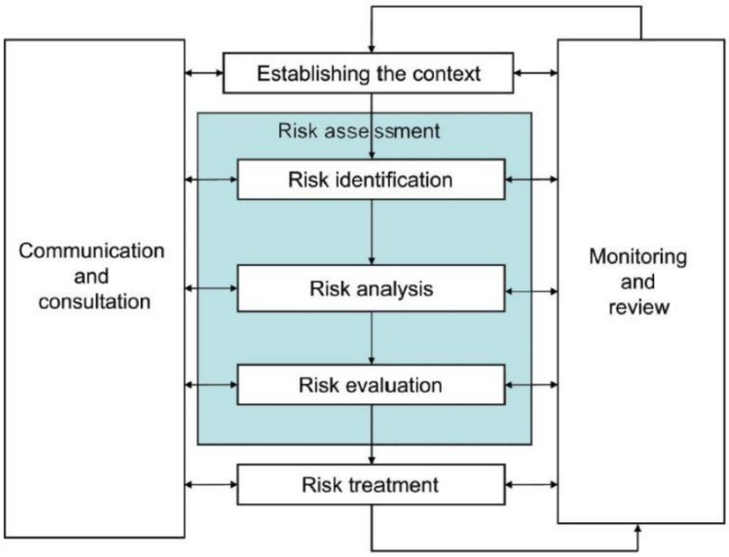

Figure 1.3: Risk management framework used in this thesis (from AS/NZS ISO-31000, 2009).

The risk of impact from volcanic hazards hazard can be expressed as a function of the hazard and vulnerability (after Blong, 2000):

$$\text{Risk} = f(\text{hazard x vulnerability}) \quad (1.1)$$

In the context of volcanology, the term *hazard* refers to volcanic phenomena with the potential to cause loss of life and infrastructure damage in a given area (Blong, 2000). Volcanic hazards are of various types, and the level of threat to humans and their livelihood depends on the vulnerability of the area exposed to the hazard (Table 1.2).

Vulnerability is the degree to which elements (e.g. people, infrastructure, system components, primary production, etc.) can be damaged due to exposure to the hazard (Blong, 2000). Thus, risk is the probability that damage to components will occur as a result of the hazard.

Table 1.2: Effects and extent of the primary volcanic hazards (adapted from Sparks and Aspinall, 2004).

Volcanic hazard	Threat to life	Threat to property	Areas affected
Tephra and pumice fall	Low except near vent; high for aviation	Variable, depends on thickness: roof collapse, bomb damage, fire, etc.	Local to international
Pyroclastic flows and surges	Very high	Very high	Local to regional
Lava flows	Low	Very high	Local
Lahars/flooding	High to moderate	High	Local to regional
Gases/acid rain	Low to moderate	Moderate	Local to regional

The risk management process begins with identifying the risk. In the context of this thesis, this step involves identifying all potential volcanic hazards within a specified area and characterising their impacts. In addition, all the elements (e.g. people, buildings, critical infrastructure, etc.) at risk from the hazard must be identified, and the potential for knock-on effects impacts, including cascade or common mode failures (AS/NZS ISO-31000, 2009). It is also important to understand how elements relate spatially and temporally to the hazard, and their potential vulnerabilities (Crozier and Glade, 2005). Identification is achieved through reviewing previous hazards that have occurred in the study area, from literature and geological investigations (Kaye, 2008). In essence, this step identifies all factors which require further investigation in the risk analysis stage (Crozier and Glade, 2005).

The risk analysis and evaluation stages are focussed on developing an understanding of the risks (AS/NZS ISO-31000, 2009) so they can be compared and ranked. This involves assessing the magnitude and frequency of volcanic hazards and the vulnerabilities of exposed elements. These assessments are either deterministic or probabilistic or a combination of both. Traditionally, deterministic methods have been used in volcanic risk assessment, such as eruption recurrence intervals or the maximum expected eruption, to assess future eruption risk. However, there is an increasing desire for systematic and probabilistic risk assessment to describe risk posed by current or future volcanic events, and to better account for evolving eruption histories, incomplete and/or short eruption histories, and volcanoes with a range of possible future eruption magnitudes and/or styles (Smith, 2004).

Probabilistic risk assessments are used to determine the probability of a hazard occurring and its associated damage from a range of scenarios, with limited subjective input. These assessments are better at handling a range of hazards, magnitudes and variable hazard frequency/return periods. An example of this type of assessment is a Bayesian Event Tree (BET). In this assessment all potential volcanic scenarios are mapped out with corresponding probabilities of occurrence (Newhall and Hoblitt, 2002). A BET illustrates the likelihood of all possible events and typical damage that will occur. To determine the degree of damage that can occur in each scenario, fragility functions can be incorporated into probabilistic risk assessment.

The vulnerability of different elements can vary significantly (Blong, 2000). Vulnerability can be quantified by probabilistic risk assessment using fragility functions (also known as vulnerability curves) to express numeric relationships between the intensity of a hazard and degree of loss, specific to each inventory class or sector (e.g. Spence et al., 2005). These functions can be developed through the observation, either in the field or in a controlled laboratory environment, of critical elements under a range of impact conditions and a numerical relationship is defined which best estimates the fragility distribution. Few studies on volcanic ashfall hazards have utilised fragility functions, mainly due to the lack of quantitative damage or loss data. Limited examples include estimating the collapse probability of residential buildings from ashfall (e.g. Blong, 2003; Spence et al., 2005). Thus, this thesis will look to inform first-order fragility models through controlled analogue experiments and thereby extend the capacity of contemporary volcanic risk assessment.

The final step in the risk management process is risk reduction. This step is aimed at reducing the hazard and/or the vulnerability of the elements within the affected area. In volcanology, reduction of hazards is not always possible and in most cases is very difficult, as they are naturally occurring events not easily controlled by humans. Therefore, it is more beneficial to focus risk reduction efforts on reducing the vulnerability of exposed elements. Vulnerability can be reduced by implementing various mitigation actions/techniques/strategies which have been developed through the integration of field and laboratory analysis. A number of actions may be considered and applied either individually or in combination to protect certain elements from impacts (AS/NZS ISO-31000, 2009). It is also imperative that decision makers and stakeholders be aware of the nature and extent of the residual risk, even after taking steps to mitigate or reduce the original risk.

1.4 ELECTRIC POWER SYSTEMS

Modern society has become increasingly dependent on a safe and reliable electricity supply to maintain national security, the health and welfare of communities, and the functionality of other vital infrastructure (e.g. telecommunications, transportation, water supplies, wastewater, etc.) and primary industry (e.g. agriculture). In the year 2000, the National Academy of Engineering in the USA compiled a list of the twenty 'marvels of science and engineering' that have had the greatest influence on the quality of life in the 20th century. The first item on the list was electrification. On a world scale, electricity is a vast array of generation, transformation, transmission, distribution and utilisation networks. Investment in this industry has a major impact on global society, world economy and the environment.

The basic function of a power system is to supply customers, both major and minor, with electrical energy as economically as possible and with an acceptable degree of reliability and quality (Billinton and Allan 1988). There are four main components of the modern electric power industry: (1) generation, (2) transmission (e.g. >110 kV by USA standards), (3) sub-transmission (e.g. 33 to 110 kV), and (4) distribution (e.g. <33 kV), as illustrated in Figure 1.4.

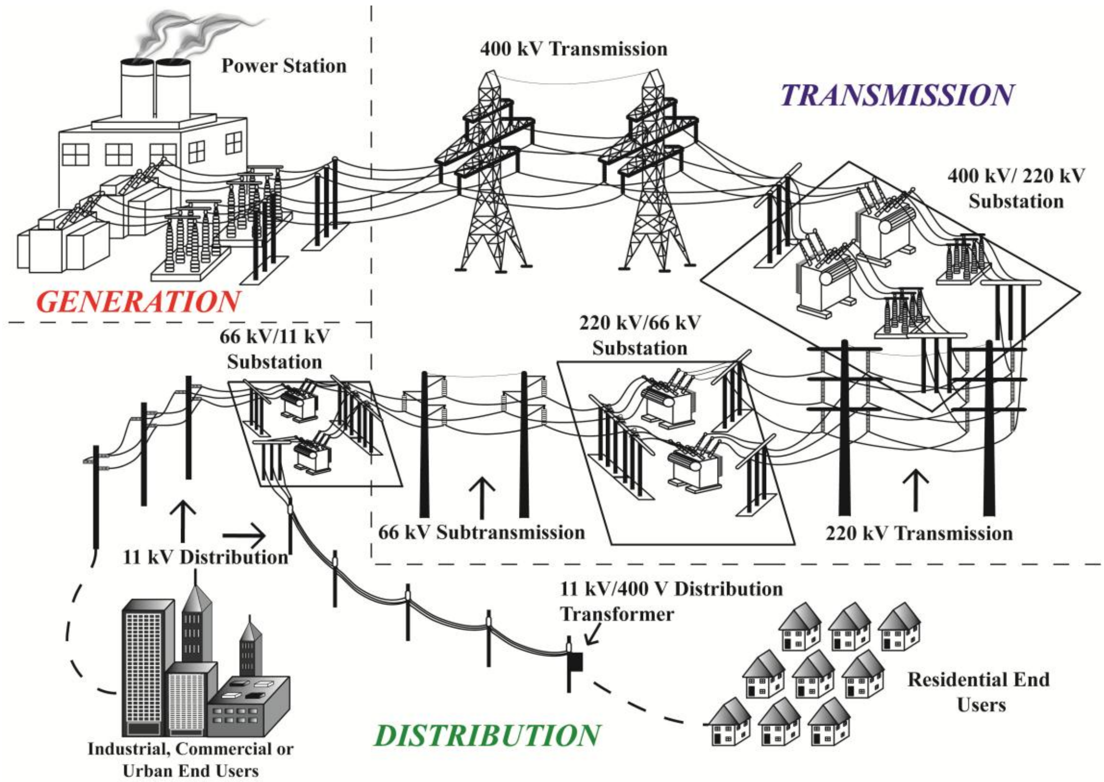

Figure 1.4: An example of a modern electric power system. Electric energy is generated at a power station (e.g. 13 kV). From here, the voltage is increased (current decreased) and the energy transmitted at 400 kV via extra-high voltage (EHV) transmission lines to a 400/220 kV EHV substation. The energy is then transmitted to a HV substation where the voltage is reduced to 66 kV. Sub-transmission lines connect the HV substations to many distribution substations located within cities, where the voltage is reduced to 11 kV and the energy finally distributed either directly to industrial plants or factories, or to local residential and commercial zones. Distribution transformers (ground or pole mounted) reduce the voltage from 11 kV to ~400/220 V (depending on the system used) for use in homes, shopping centres, and other local loads (adapted from Karady, 2007).

Generation sites transform the stored energy present in fossil (oil, coal, natural gas, etc.), nuclear, and renewable (geothermal fluids, wind, solar or water) fuels into electric energy. A typical alternating current generator produces a voltage of around 11 to 25 kV. This voltage is increased by a step-up transformer (increase in voltage, decrease in current) to facilitate the transmission of power over large distances by reducing losses. The transmitted power then passes through a ‘switchyard’ which is a facility dedicated to feeding power to different sections of the system (voltage is neither increased nor decreased at switchyards). Once the power reaches a substation located on the edge of a town or city, the voltage is reduced for integration into a sub-transmission system where power is fed to many distribution substations (e.g. within cities). At the distribution substation, the voltage is reduced again and the power fed into a localised distribution system of overhead lines or underground cables. Large industrial plants and factories are usually supplied directly by a sub-transmission line or dedicated distribution line. Before residential consumption, however, the line voltage is reduced to ~400/220 V (depending on the system used) by distribution transformers that are commonly mounted on distribution poles or in ground placed kiosks.

1.4.1 Outdoor insulators for HV alternating current (HVAC) systems

High voltage direct current (HVDC) lines are used to transmit large amounts of energy over long distances or through waterways. However, a three-phase AC system (generally, 60 Hz operating frequency in North and much of South America and Japan, and 50 Hz in nearly all of the rest of the world) is used for most transmission and distribution lines (Karady, 2007). In light of this, the thesis focuses on insulators intended for AC systems and apparatus. Accordingly, any reference herein to HV insulators denotes those intended for outdoor HVAC overhead lines.

Although line insulators are only a small fraction of the apparatus or line cost, line performance is highly dependent on insulator integrity. Insulator failure may cause permanent equipment damage and long-term outages, and the potential financial losses to power authorities highlights the importance of reliable insulator design and selection for all operating environments (IEC 60815-1, 2008).

Insulators come in many shapes, materials and sizes. The first transmission line insulators were built with bisphenol epoxy resin in the mid-1940s (Karady and Farmer, 2007). Generally, the upper part of insulator sheds is smooth to allow rain washing and cleaning of the surface. On standard or high-creepage (anti-fog) insulators (e.g. fog or bowl profiles), the lower part is often corrugated to prevent wetting and provide a longer protected creepage path (the shortest distance, or sum of shortest distances, between electrodes measured along the insulating surface). This is significant as the performance of insulators for polluted environments is most often expressed solely in terms of the creepage distance necessary to withstand the polluted conditions under the system voltage (IEEE Std 1313.2, 1999; IEC 60815-1, 2008).

The insulator has to withstand normal operating voltages. The system voltage is defined as the root mean square (rms) voltage between the conductors, also called line-to-line voltage. The voltage between the phase conductor and earth, called line-to-earth voltage, is equal to the line-to-line voltage divided by the square root of three. To account for over voltages experienced during switching and changing loads, a +10% safety factor is typically applied (Farzaneh and Chisholm, 2009). Thus, a general approximation of the phase-to-earth insulator requirement for a 220 kV system is determined using Equation 1.2:

$$1.1\frac{220\ \mathrm{kV}}{\sqrt{3}} \cong 140\ \mathrm{kV} \tag{1.2}$$

The resulting single-phase voltage calculation, together with an evaluation of the installation site's pollution severity (discussed in Section 1.4.2) and the local environmental conditions, are used to select the appropriate profile and number of insulators/discs/units (a function of creepage distance) to be used for the line. The performance of an insulator is commonly assessed by measuring its dry flashover voltage (Karady and Farmer, 2007). By definition, flashover is a disruptive discharge through air, around or over the surface of solid or liquid insulation, between parts of different potential or polarity (IEEE Std 1410, 2004). Dry flashover tests do not cause any damage to the insulators themselves, and as the flashover is through the air, insulators are considered self-restoring (i.e. the air's dielectric properties are restored following flashover). For a porcelain insulator, the required dry flashover voltage is about 2.5–3 times the rated voltage (Karady and Farmer, 2007).

1.4.1.1 Ceramic (porcelain and toughened glass)

Porcelain and/or toughened glass are the most frequently used materials for insulators (Karady and Farmer, 2007). Porcelain materials are typically made up of varying proportions of clay, feldspar and quartz minerals. For glass designs, silica, soda ash, dolomite, limestone, feldspar and sodium sulphate are most commonly used (Looms, 1988).

1.4.1.2 Non-ceramic

The first non-ceramic (composite polymer) insulators, with fibreglass rods and rubber weather sheds, appeared in the mid-1960s. Non-ceramic insulators have a dirt and water repellent (hydrophobic) surface that reduces pollution accumulation and wetting. Polymeric insulators have been increasingly used for both distribution and transmission voltage ranges for the last few decades as, in general, the contamination performance of non-ceramic insulators is better than those of ceramic equivalents (Karady, 1999; Hackam, 1999; IEEE 1523, 2002; IEC 60815-3, 2008).

1.4.2 Pollution severity

Pollution-induced insulator flashover has been a problem since the first electric power systems (Baker et al., 2009). The phenomenon has been extensively studied (e.g. CIGRE TF 33.04.01, 2000; Farzaneh and Chisholm, 2009 and references within), as have a number of other airborne pollutants which can cause flashover (Table 1.3).

Table 1.3: Common types of airborne pollution capable of causing pollution-induced flashover on electrical insulators (adapted from IEEE Std 957, 2005).

Contaminant		**Source and Explanation**
Salt		Insulators located near a body of salt water (e.g. sea or ocean) are prone to salt contamination from wind-blown spray. Salt pollution may also originate from highways or elevated roadways where salt is used to melt snow and ice. Substantial salt deposits may accumulate during long periods of dry weather.
Cement/lime		Accumulations of lime or cement easily bond to insulator surfaces and often form a hard crust which is very difficult to remove. Cement plants, construction sites and rock quarries provide sources of ionic-rich contamination in the form of cement and or lime ($CaCO^3$).
Dust	Earth	Earth dust arises from agricultural enterprises (e.g. ploughing fields), earth moving at construction sites, etc.
	Fertiliser	Fertiliser dust is emitted from the application of fertiliser during farming and from fertiliser manufacturing plants.
	Metallic	Metallic dust can stem from various mining and mineral handling processes.
	Coal	Coal mining and coal handling operations and industrial burning of coal are major sources of coal dust. Soot and fly-ash resulting from the burning of coal may form compounds that adhere firmly to insulator surfaces.
	Feedlot	Provender dust and earth dust stirred by animals in large feedlots can settle on nearby insulators during periods of dry weather.
Smog (combustion emissions)		In urban areas, emissions from combustion automobiles and locomotives (e.g. diesel trains) and other industrial activities introduce a significant amount of particulate matter into the environment and pose a pollution hazard to insulators.
Chemical		Atmospheric pollutants from a wide variety of industrial chemical processes and aerial spraying of agricultural chemicals and fire-fighting chemicals (e.g. borate) can form considerable deposits on insulators. The characteristics of these chemical contaminants vary widely.
Defecation		Bird excrement can create a conductive path between the HV conductor and the earthed tower structure leading to 'bird streamer' flashover.
Smoke		Industrial and agricultural burning or wildfires can, with other compatible conditions (such as moisture and humidity), cause the resulting contamination to accumulate on HV insulators.

Traditionally, power engineers have used quantitative methods to measure the severity (potential for flashover) of soluble and non-soluble airborne pollutants which accumulate on HV insulators (IEC 60815-1, 2008).

1.4.2.1 ESDD

Equivalent salt deposit density (ESDD), expressed in mg/cm^2, is one of the most common parameters used to measure the pollution severity on contaminated insulators. An internationally recognised standard parameter, the ESDD or 'Solid Layer' method equates the amount of sodium chloride (NaCl) required to yield the same conductivity as the insulator contaminant when dissolved in the same volume of water (CIGRE TF 33.04.03, 1994). From the conductivity, volume, and temperature of the solution and the area from which the sample was collected, ESDD can be calculated. ESDD values are typically classified into insulator specific site pollution severity indexes provided in international standards, guides or technical brochures and/or bulletins, as shown in Table 1.4.

Table 1.4: General site severity and its definition per CIGRE Technical Bulletin 63 (1991) and IEEE Std 1243 (1997).

Site Severity	ESDD (mg/cm^2)	
	CIGRE	IEEE
None	0.0075-0.015	
Very light	0.015-0.03	0-0.03
Light	0.03-0.06	0.03-0.06
Average/moderate	0.06-0.12	0.06-0.10
Heavy	0.12-0.24	>0.10
Very Heavy	0.24-0.48	
Exceptional	>0.48	

1.4.2.2 NSDD

The non-soluble deposit density (NSDD) is another internationally recognised pollution parameter that is used to quantify the amount of non-soluble matter on contaminated insulators (also expressed in mg/cm^2). The sensitivity of salt deposit density is higher on insulator performance than that of NSDD (Ramos et al., 1993). However, other studies have shown that inert, non-soluble pollution can greatly reduce the flashover voltage of HV insulators (Ishii et al., 1996; Sundararajan and Gorur, 1996). Insoluble deposits do not contribute directly to conductivity but can affect (1) the run-off rate of soluble material, (2) the hydrophobicity of the insulator surface, (3) the evaporation rate of the wetted layer, and (4) the local electric field strength (Farzaneh and Chisholm, 2009).

1.5 INSULATOR FLASHOVER

Insulator flashovers result in power outages that are expensive and therefore undesirable. For example, flashover across a line insulator may cause a 250 ms trip-out before an auto-reclose system reconnects the circuit. This is sufficient time to shut-down a paper machine, resulting in hours of down time, possible equipment damage, and up to $50,000 in lost production (IEEE Std 1523, 2002).

Johnston (1997) identified key factors influencing volcanic ash-induced insulator flashover (Figure 1.4). Once a volcanic ash deposit becomes conductive it provides a path for electric 'leakage' current to flow between the phase conductor (line) and the ground (earth). This leakage current causes a heating effect which dries out parts of the ash layer, giving rise to 'dry bands' on the insulator which interrupt the flow of leakage current. The dry bands are bridged by arcs which cause a surge of leakage current. Ultimately, the arcs or grow in size to span the whole of the insulator surface and a line-to-earth fault occurs (Baker et al., 2009).

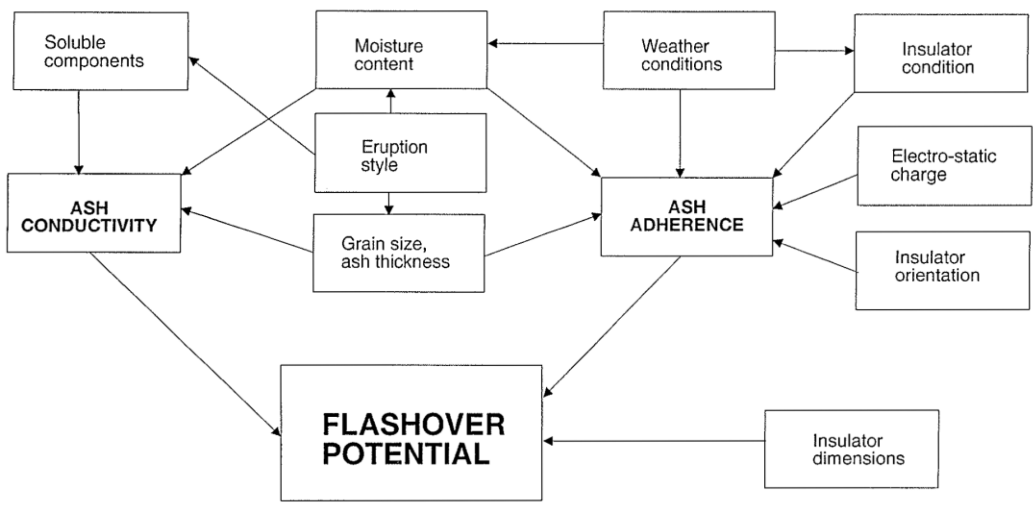

Figure 1.5: Factors influencing volcanic ash-induced insulator flashover (from Johnston, 1997).

1.5.1 Flashover mechanism

Flashover is produced by the application of voltage wherein the breakdown (flashover) path becomes sufficiently ionized to maintain an electrical arc (IEEE Std 1410, 2004).

1.5.1.1 Hydrophilic surfaces

Hydrophilic surfaces attract and retain water molecules (Starov et al., 2007). The flashover process around or over porcelain and glass (hydrophilic) surfaces is believed to occur in 6 phases (adapted from IEC 60815-1 (2008) and Farzaneh and Chisholm (2009)):

Phase 1: A dry insulator string has been uniformly coated in dry, fine-grained (e.g. <0.1 mm particle diameter) volcanic ash. As the dry contaminant is non-conducting, no sizeable leakage current will flow over the insulators' surfaces.

Phase 2: As moisture gathers on the insulators' surfaces via absorption, condensation or precipitation, the soluble component of the ash dissolves, forming a conducting solution through which leakage current flows (Figure 1.6a).

Phase 3: The leakage current steadily builds up and, in time, will generate enough heat in areas of high current density (e.g. near the pin of each cap-and-pin disc insulator in a chain) across the ash layer to induce a rate of evaporation greater than the rate of moisture accumulation. Prolonged evaporation leads to the formation of dry spots (Figure 1.6b). These dry spots offer a much larger resistance than the remaining conducting solution, thus almost the entire applied voltage falls across the dry spot to create an exceedingly non uniform voltage distribution (kV/m) along the insulator string.

Phase 4: The voltage gradient across the dry zones will subsequently exceed the dielectric strength of the surrounding air to cause small arc discharges. Further discharging across the dry spots increases the rate of evaporation, which in turn leads to an enlargement or coalescence of the dry spot(s) to form a single dry band (Figure 1.6c).

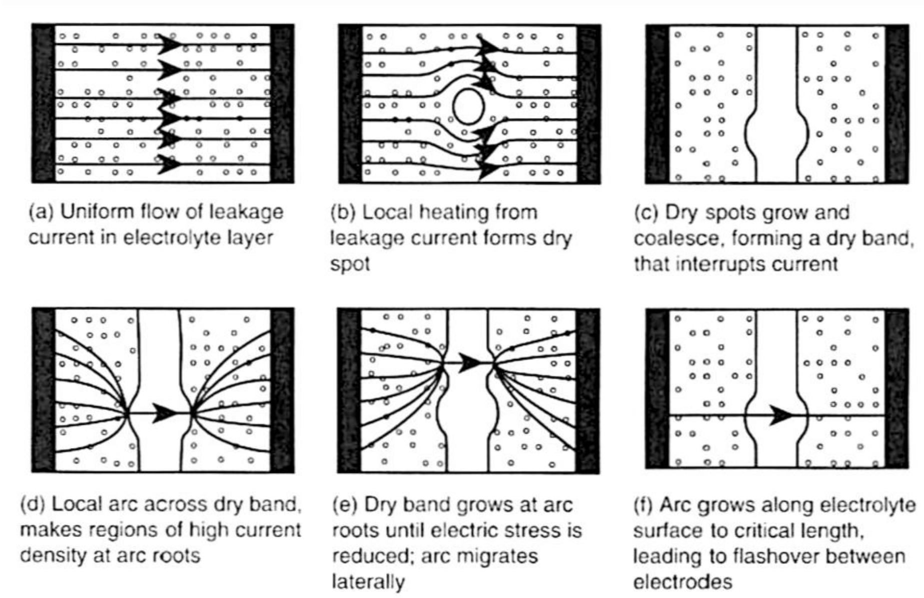

Figure 1.6: Process of flashover across a hydrophilic surface (from Farzaneh and Chisholm, 2009).

Phase 5: Areas of higher current density result in increased heating effects and cause the dry band to increase in size until it becomes too wide (critical width) for discharges to exist and a breakdown occurs, forming a localised arc across the dry band (Figure 1.6d). This causes a surge of leakage current each time the dry bands on an insulator spark over.

Phase 6: The arc may migrate laterally along the dry band to an area of higher electric field stress (Figure 1.6e). If the resistance of the still wet and conductive part of the pollution layer is low enough, the arcs bridging the dry bands are sustained and may finally continue to extend along the insulator, bridging more and more of its surface. This in turn decreases the resistance in series with the arcs, increasing the current and permitting them to bridge even more of the insulator surface. Ultimately, the insulator surface is completely bridged and a line-to-earth fault (flashover) is established. (Figure 1.6f).

1.5.1.2 Hydrophobic surfaces

A different model exists for hydrophobic (water repelling) surfaces such as those on composite polymer insulators or ceramic insulators with a room temperature vulcanising (RTV) silicone rubber coating. In summary, pollution flashover begins with pollution (e.g. volcanic ash) building up on the surface of non-ceramic weathersheds. Wetting produces distinct water droplets (as opposed to a film, as is the case on hydrophilic surfaces) (Figure 1.7a) on the surface and these droplets slowly migrate to the pollutant and subsequently dissolve the soluble material in the contaminant (Figure 1.7b). These wetted areas coalesce and initiate a leakage current (Figure 1.7c). The leakage current dries the insulator surface where areas of current density are highest (e.g. near the pin on standard cap and pin insulators) and increases surface resistance between wet regions. Electric fields between the wet regions increase to form small spot discharges (Figure 1.7d). With time, the increased arcing activity decreases the hydrophobicity of the insulator surface, creating larger wet regions and an intensification of discharges (Figure 1.7e). These discharges continue to increase until flashover occurs (Figure 1.7f).

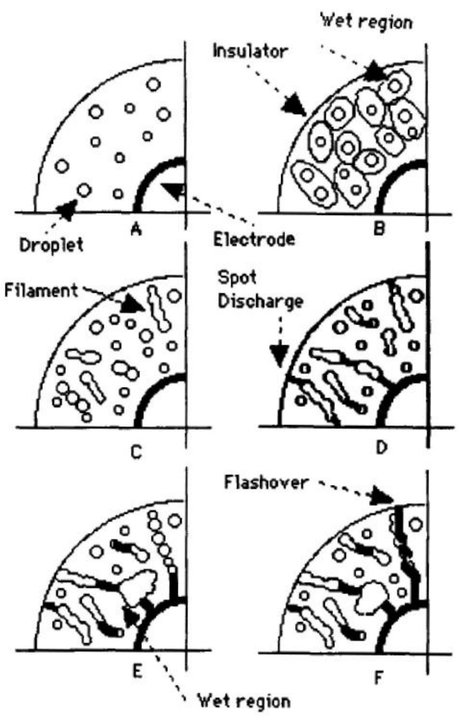

Figure 1.7: Development of flashover on a hydrophobic surface (from Karady, 1999).

Further information on the flashover mechanism on hydrophobic surfaces can be found in Karady (1999), Karady et al. (1995) and Farzaneh and Chisholm (2009). However, given the dynamic nature of hydrophobic surfaces and the resulting complex interactions with pollutants and wetting agents, no generally accepted model of pollution flashover exists for hydrophobic insulator surfaces (IEC 60815-1, 2008).

1.6 ELECTRICAL TESTING PROCEDURES

Insulator pollution tests have long been used to characterise the pollution performance (dielectric strength) of HV insulators. There are three main types of electrical test methods (after IEC 60507 (1991) and IEEE Std 4 (1995)):

1) *Salt-fog* tests, where energised insulators are mounted in a specialised testing chamber and subjected to a salt aerosol with a conductivity ranging from 4,300 to 200,000 μS/cm.
2) *Clean-fog* tests, where insulators are pre-contaminated with a salt deposit density between 0.03 and 0.4 mg/cm^2 and then wetted with steam or water aerosol.
3) *Heavy rain* tests, where water of a specific conductivity (typically 100 μS/cm) is applied at a controlled rate for a period of several minutes before energising the insulator.

Previous studies have used variations of the clean-fog test. Nellis and Hendrix (1980) performed withstand or up-and-down tests on a number of insulator specimens; where a voltage level is maintained for a specified period of time (e.g. 1 hr). The voltage is increased by small increments (e.g. 4-5%) and held for allotted periods of time until disruptive discharge or a withstand occurs. If a flashover occurs, the applied voltage is then lowered to about 85% of the previous flashover voltage, and the withstand procedure continued until a 50% flashover value (indication of insulator performance) is determined (IEEE Std 4, 1995).

1.7 ASHFALL HAZARDS TO ELECTRICAL INFRASTRUCTURE

Limited information indicates that electric power networks appear particularly vulnerable to disruption from volcanic ashfalls (Nellis and Hendrix, 1980; Blong, 1984; Matsuoka et al., 1995; Johnston, 1997; Wilson et al., 2009). There has been a general lack of empirical evidence to explain the impacts on, and the length of recovery for electric power systems over a range of ash contamination severities (e.g. depths, ESDD, NSDD, etc.) and ash properties (such as grain size, composition, soluble salt content, etc.) to support the development of robust methods for risk analysis and evaluation (e.g. using fragility functions). To the best of the author's knowledge, following the 1980 Mount St Helens eruption, engineers from BPA were the first to document ashfall impacts to electrical infrastructure and carry out semi-quantitative analyses of system vulnerability and insulator flashover (e.g. Buck and Connelly, 1980; Nellis and Hendrix, 1980). Blong (1984) mentioned other anecdotal instances of power systems impacts from ashfalls, however, no quantitative studies were available until 1995, when Japanese engineers at NGK (Nippon (Japan) Gaishi (Insulator) Kaisha (Company)) investigated the flashover voltage of insulators artificially contaminated with volcanic ash from national volcanoes. Whilst these studies provide reasonable estimates, they highlight the lack of empirical data for effective quantitative risk assessment.

It is generally accepted that where ash thicknesses are the same, finer ash (e.g. <0.1 mm) will cause greater problems than coarser ash (e.g. >1 mm), as it has greater adherence properties, more easily penetrates electrical equipment, and its higher surface area should lead to greater electrical conductivity when moist (Wilson et al., 2009). Previous work has suggested dry volcanic ash is not likely to cause failure to electrical distribution networks (Nellis and Hendrix, 1980; Bebbington et al., 2008), and heavy rain or wind will wash ash from lines and insulators, eliminating the hazard. Thus, in order to reduce the uncertainty surrounding ash-induced impacts to electric power systems, a systematic assessment of these parameters is required to assess the vulnerability (hazard intensity/damage ratio) of specific system apparatus to volcanic ash contamination.

1.8 THESIS GOALS AND OBJECTIVES

The ultimate goal of the thesis is to identify, assess, evaluate, and reduce the risk of volcanic ashfall impacts to electric power systems as a part of holistic risk management practise. Insulator flashover on transmission systems is the most common impact during and following ashfalls in the world. Although anecdotal evidence and limited experiments provide some understanding of flashover processes, a systematic examination of this problem has not been conducted to date. Important uncertainties remain poorly investigated, such as the effects of different ash compositions, textures, and surface coatings on electrical system responses. Ashfall thickness (depth) is the common ash hazard intensity parameter used by volcanic scientists for damage estimation (e.g. Connor et al., 2001; Bonadonna et al., 2005; Jenkins et al., 2009), yet several other physical, chemical, electrical, and environmental parameters may determine the ash hazard to power system apparatus. As risk managers continue to demand a more quantitative approach to understanding the impacts from volcanic ashfall hazards, and given the limited understanding for the potential for loss of system integrity, this thesis uses empirical data from analogue laboratory experiments and available literature to assess the vulnerability of essential electric power system components to volcanic ashfall contamination and assist the development of mitigation strategies. Ash-induced insulator flashover is the most common impact, so it is the primary focus of the thesis and is addressed with the following objectives:

1) Identify and review the known impacts to electric power systems from volcanic ashfall, develop mitigation strategies, and explore the numeric relationships between intensity of ash hazard (e.g. ash thickness) and probability of insulator flashover;

2) Investigate the physical, chemical, and electrical properties of volcanic ash most influential in increasing electrical conductivity and therefore the hazard intensity of volcanic ash;
3) Measure the pollution severity of volcanic ash using traditional pollution monitoring methods within the field of electrical engineering (e.g. ESDD and NSDD);
4) Quantify the variables influencing volcanic ash-induced insulator flashover and measure the pollution performance (flashover voltage and/or dielectric strength) of different HVAC insulators subjected to a range of contamination severities;
5) Analyse precursor sinusoidal leakage current and partial discharge activity leading up to insulator flashover to evaluate the potential for real-time pollution monitoring (risk assessment) techniques.

1.9 THESIS STRUCTURE

The body of the thesis is comprised of five chapters, each one a scientific manuscript which has been accepted by, or prepared for submission to, an international peer-reviewed journal. Vulnerability of electric power systems to volcanic ashfall hazards is approached by reviewing known impacts to the three components of the modern power network (Chapter 2). A direct resistivity method is presented in Chapter 3 to better understand the electrical properties most influential in promoting the electrical conductivity (hazard intensity) of volcanic ash. The few studies which have characterised volcanic ash electrically (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Matsuoka et al., 1995) have focussed on the ash's ESDD and NSDD. Thus, to provide a contemporary analysis of multiple ash samples and a review of the techniques' limitations, Chapter 4 presents the results from a suite of ESDD/NSDD measurements. Using the knowledge gained from electrical analyses, Chapters 5 and 6 contain the results from flashover voltage, dielectric strength, leakage current and partial discharge measurements during analogue laboratory power-frequency tests on contaminated HV insulators.

Chapters 2 to 6 are each preceded by an outline of the intended journal for publication, publication status of the manuscript at the time of thesis submission, and the main purpose of the manuscript in fulfilling the thesis objectives. The methodologies, applications and results described in the chapters are direct outcomes of the author's own research, however, contributions from co-authors have been invaluable and their input is also detailed in the co-authorship forms found after the thesis abstract. The content of each chapter and appendix has not been modified from the versions accepted or submitted to journals.

Appendices 1, 2, and 3 are included in the thesis to provide additional research content and the primary data which support the chapters, the discussion and the conclusions. They also show evidence of wider analysis of volcanic ash vulnerability assessment on critical infrastructure.

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Chapter 2: Potential impacts from tephra fall to electric power systems: A review and mitigation strategies

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The literature review component of Chapter 2 was adapted and expanded by Mr. Wardman from prior work done by Wilson et al. (2009). Mr. Wardman wrote the manuscript. Dr. Thomas Wilson contributed significantly to refining and developing the manuscript while co-authors Prof. Pat Bodger, Prof. Jim Cole and Dr. Carol Stewart offered useful discussion and review of the manuscript.

Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all.

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- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work;
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Name: *Thomas Wilson* Signature: Date: *28 March 2013*

Chapter 2

Potential impacts from volcanic ashfall to electric power systems: A review and mitigation strategies

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OVERVIEW

This chapter reviews the known impacts to electric power systems from volcanic ashfall hazards and provides system operators and/or decision makers with potential mitigation strategies against ash-induced disruption of power supply. The manuscript fills a major knowledge gap in volcanic impact assessment for electrical infrastructure and, to the authors' knowledge, is the first to provide cleaning advice on how to effectively remove ash from contaminated HV apparatus.

2.1 ABSTRACT

Modern society is highly dependent on a reliable electricity supply. During explosive volcanic eruptions, ash contamination of power networks (systems) can compromise the reliability of supply. Outages can have significant cascading impacts for other critical infrastructure sectors and for society as a whole. This chapter summarises known impacts to power systems following ashfalls since 1980. The main impacts are: (1) supply outages from insulator flashover caused by ash contamination; (2) disruption of generation facilities; (3) controlled outages during ash cleaning; (4) abrasion and corrosion of exposed equipment; and (5) line (conductor) breakage due to ash loading. Of these impacts, insulator flashover is the most common disruption. The review highlights multiple instances of electric power systems exhibiting tolerance to ashfalls, suggesting that failure thresholds exist and should be identified to avoid future unplanned interruptions. To address this need, we have produced a fragility function that quantifies the likelihood of insulator flashover at different thicknesses of ash. Finally, based on our review of case studies, potential mitigation strategies are summarised. Specifically, avoiding ash-induced insulator flashover by cleaning key facilities such as generation sites and transmission and distribution substations is of critical importance in maintaining the integrity of an electric power system.

2.2 INTRODUCTION

Electricity is the 'life blood' of modern society (Lawrence, 1988). Increasing demand for electricity has been driven by population growth and increasing use of electrically powered technologies. Electricity supply is arguably the most essential contemporary infrastructure, especially considering the dependencies of other infrastructure groups on electric power to maintain functionality (Figure 2.1). Given that 9% of the world's population is estimated to live within 100 km of a historically active volcano (Horwell and Baxter, 2006), and many of these areas are experiencing significant population and economic growth, their exposure and vulnerability to the impacts of volcanic hazards is increasing (Johnston et al., 2000). Effective disaster risk reduction and infrastructure management thus makes it imperative that system operators understand the potential impacts from natural disasters and take the necessary precautions to avoid unintended interruptions.

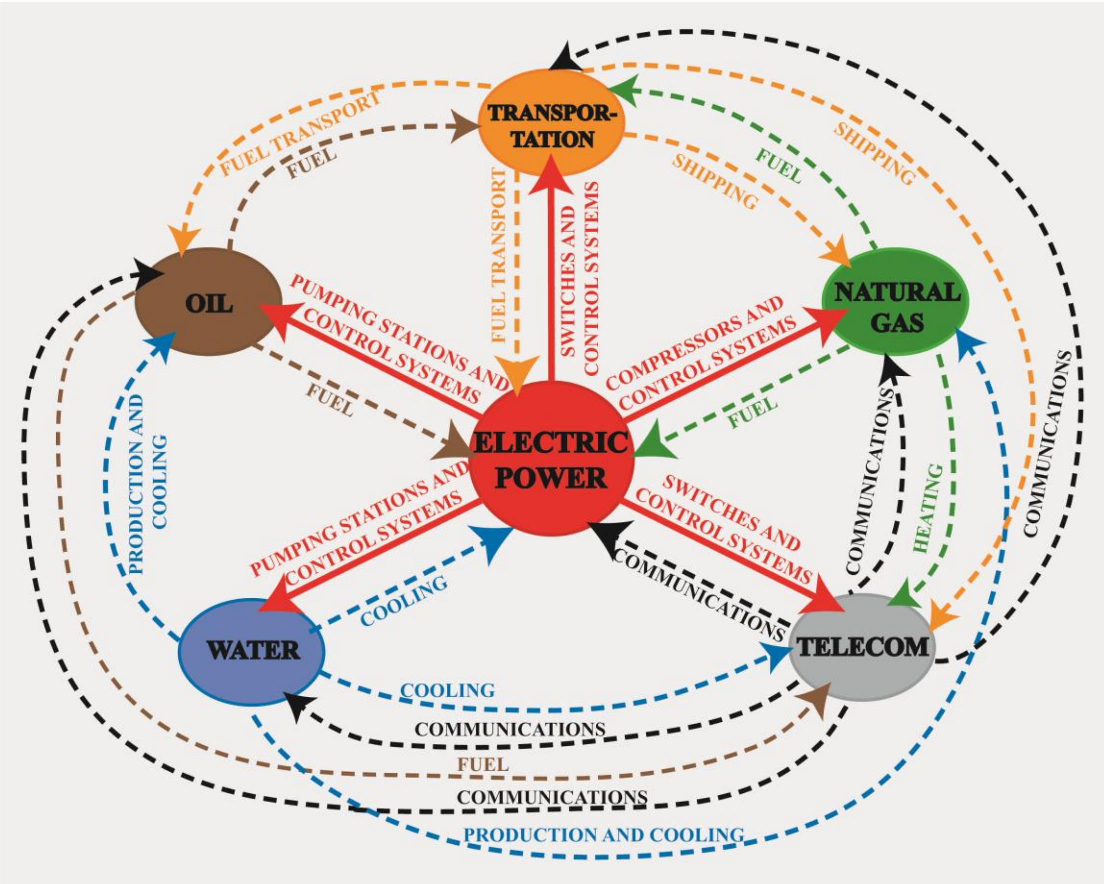

Figure 2.1: Schematic diagram illustrating some of the interdependencies between critical infrastructure systems (adapted from Rinaldi et al., 2001).

Although pyroclastic flows and surges, sector collapses, lahars, and ballistic blocks are the most destructive and dangerous of explosive eruption products (Baxter, 1990; Hansell et al., 2006; GFDRR, 2011), ashfall is the most widespread volcanic phenomenon. Volcanic ash is the product of explosive volcanic eruptions and is composed of pulverised fragments of rock, minerals, and glass (SiO_2) with a particle diameter smaller than 2 mm. Fine-grained ash (defined here as <1 mm particle diameter), can be dispersed large distances by winds. Even in small eruptions, thousands of square kilometres may be impacted by ashfalls (Johnston et al., 2000). Extensive, above-ground, corridor systems of electrical apparatus used in power generation, transformation, transmission, and distribution often stretch hundreds to thousands of kilometres, making them highly exposed to such ashfalls. This high level of exposure emphasises the need to understand the vulnerabilities of power systems in both proximal and distal locations.

Volcanic ash can cause disruption to electricity generation and supply in the following ways (expanded from Wilson et al., 2009):

1. High voltage (HV) insulators (porcelain, glass or composite) are electrical hardware designed to mechanically support and electrically isolate energised lines or apparatus from earthed (bonded with the ground) structures such as steel towers or wooden poles. During humid conditions such as light rain, fog, or mist, wet deposits of volcanic ash on insulators can initiate a leakage current (small amount of current flow across the insulator surface) that, if sufficient current is achieved, can cause 'flashover' (the unintended electrical discharge around or over the surface of an insulator). If the resulting short-circuit current is high enough to trip the circuit breaker then disruption of service will occur. The presence of leakage current is due to the electrical conductivity of the wet ash, which is influenced by (1) moisture content, (2) soluble salt content, (3) compaction and, to a lesser extent, (4) grain size (discussed further in Chapter 3). Ash-induced flashover on or across external insulation (bushings) for power transformers can burn, etch or crack the bushings irreparably and potentially damage the internal components (e.g. windings) of the transformer;

2. Controlled outages of vulnerable nodes (e.g. generation facilities and/or substations) or circuits until ashfall has subsided or for offline (de-energised) cleaning of equipment.

3. The hardness and angularity of volcanic ash make it highly abrasive. Volcanic ash can accelerate normal wear by eroding and scouring metallic apparatus, particularly moving parts such as

water and wind turbines at generation sites and cooling fans on power transformers;

4. The high bulk density of some volcanic ash deposits can cause line breakage due to ash loading. This is most hazardous when the ash and/or the lines are wet and usually following at least 10 mm of ashfall. Fine-grained ash adheres to lines and structures (e.g. wooden poles and steel towers) most readily. Volcanic ash may also load overhanging vegetation, causing it to fall onto lines which can bridge (make contact between) phases (lines) or cause line breakage and/or damage to structures. Snow and ice accumulation on lines and overhanging vegetation further exacerbates the risk;

5. Ash ingress can block air intakes causing a reduction of air intake quality and quantity for turbines and cooling and heating, ventilation, and air-conditioning (HVA) systems at generation sites and substations. This may lead to a reduction in efficiency, precautionary shut-down (to avoid damage), damage, or even failure. Volcanic ash could potentially abrade, clog, and corrode thermal turbines and control systems following ingestion, although these impacts have not been recorded.

This chapter provides an overview of the recorded impacts to power systems from volcanic eruptions since 1980 (Table 2.1). We have compiled data from existing literature, personal communications with system operators during meetings and semi-structured interviews, and field observations from around the world to summarise electricity system performance following ashfalls and successful mitigation strategies. Given the lack of existing data, a fragility function was developed to provide an estimate for the likelihood of insulator flashover at different thicknesses of wet or dry ash. This study ultimately aims to inform the volcanological, hazard mitigation and electrical engineering communities of the potential adverse impacts arising from ash contamination and provide best-practise and impact-specific mitigation advice.

Table 2.1: General information on the nine volcanoes used as case studies within this chapter (data compiled from Siebert and Simkin, 2002).

Volcano	Country	Year(s) of Case Study Eruption	Volcano Type	VEI	Ash Composition
Mount St Helens	USA	1980	Stratovolcano	5	Dacite
Redoubt	USA	1989/90	Stratovolcano	3	Andesite
Rabaul	Papua New Guinea	1994	Caldera	4	Andesite
Soufrière Hills	Montserrat (U.K.)	1995-2011	Stratovolcano	3	Andesite
Ruapehu	New Zealand	1995/96	Stratovolcano	3	Basaltic-Andesite
Chaitén	Chile	2008	Caldera	4	Rhyolite
Pacaya	Guatemala	2010	Scoria Cone	3	Basalt
Tungurahua	Ecuador	1999-2010	Stratovolcano	3	Andesite
Shinmoe-dake	Japan	2011	Shield	3	Andesite

2.2.1 Research context

Over the past 15 years our international research group led by the University of Canterbury and GNS Science, New Zealand has aimed to undertake a sustained and systematic approach to volcanic impact assessment in critical infrastructure (e.g. electricity; see Wilson et al., 2012 for more information). Meetings and interviews were carried out with infrastructure managers, and operations and maintenance staff at affected facilities. The interviews followed an extensive group of prompt questions that were used to steer the conversation, and touched upon the main topics of interest for research, including: The general impacts of ashfall on the sector; actions taken in response to ashfall; ash clean-up operations; emergency management plans; and interdependency issues. Interviews were semi-structured in nature to allow for more open exploration and discussion around the various topics that were brought up in conversation.

2.2.2 Critical components of a power system

For this review we have simplified the components of modern electricity systems into a) generation facilities, b) transmission and distribution components (insulators, lines, towers, poles, low voltage (e.g. <33 kV) transformers, etc.), and c) substations and switchyards.

2.3 DIRECT IMPACTS TO POWER SYSTEMS

2.3.1 Case studies

The following section summarises impacts from ashfalls to the three aforementioned components of a power system using impact assessment case studies carried out on nine eruptions (refer to Table 2.1 for more detail): Mount St Helens, USA. (1980); Redoubt, USA. (1989/90); Rabaul, Papua New Guinea (1994); Ruapehu, New Zealand (1995/1996); Tungurahua, Ecuador (1999-2010); Chaitén, Chile (2008); Soufrière Hills, Montserrat (1995-2011); Pacaya, Guatemala (2010); and Shinmoe-dake, Japan (2011). The review has been organised by impact type within each sector of the modern power system.

Ideally, we would have provided information on the physical (e.g. grain size distributions, particle morphology, etc.), chemical (e.g. bulk rock chemistry, soluble salt content, etc.), and electrical properties (e.g. conductivity) of the ash found at specific impact sites for each of the eruptions. This would allow analysis of properties most likely to lead to power system impacts. However assembling this information is extremely challenging because: (1) information on properties at the specific locations where power systems have been impacted is rarely reported by power system personnel. Consequentially, we rely on studies by other volcanological authors who have not collected samples at the sites of affected power systems or analysed for electrical properties; (2) some explosive eruptions examined within this study have durations of months to years, making it difficult to sample any one deposit (e.g. Soufrière Hills and Tungurahua); (3) samples rapidly leach and immediate weathering following deposition makes it hard, if not impossible, to retrospectively sample representative from specific impact-sites; and (4) the exact dates and specific locations of impact(s) on long, expansive power system assets are, in most cases, unknown. To avoid broad assumptions about the electrical properties of the ashes in the following case studies, and in the absence of site-specific data, ash thickness has been estimated from isopach maps and used here where available.

2.3.1.1 Generation

Accelerated wear at hydroelectric (HEP) sites

The 1995/96 eruption of Mt Ruapehu deposited roughly 7.6 million cubic metres of ash on the Rangipo HEP catchment (Meredith, 2007). This caused high levels of suspended ash in the Tongariro River. In the seven months following the initial eruption, an estimated 5 t of ash had passed through the system and approximately 15 years worth of normal wear had been experienced by the turbines (Meredith, 2007). Pitting and accelerated erosion was experienced by all generation equipment that came in contact with the ash-laden water.

Approximately one year after the eruption, the 120 MW plant halted operations to carry out repairs to its two turbines and all auxiliary components, causing an estimated loss of generation in excess of NZ$12 million (Johnston et al., 2000). To combat the effects of erosion and pitting, a protective coating was applied to turbine components – runner blades, labyrinth seals, wear rings, band seal, cheek plates, and wicket gates. A hard coating (tungsten carbide powder) was applied to those components considered most critical to the system (e.g. crown, blades, and band seal) while a soft coating (polyurethane) was applied to most of the other parts of the runner. As of 2007, the repaired turbines had been operating efficiently with minimal wear (Meredith, 2007).

The 156 MW Agoyan HEP faciility, located 5 km east of the city of Baños in Ecuador, is the second most important generation facility in the country (Hall et al., 1999). Since the onset of intermittent volcanic activity from Tungurahua volcano in 1999, very little ash has fallen at the dam site and on the few occasions when ash has fallen at Agoyan, the dam has operated normally. However, during October 1999 and August 2006, large volumes of ashfall (>100 mm) fell on Baños and the local municipality deemed the community risk too great for people to remain in the town. The heavy amount of ashfall resulted in the evacuation of Baños residents and closure of local utilities, including the dam.

However, while the dam turbines, generators, and control house are located in a zone of low-frequency ash fallout, the Pastaza catchment of the dam is often exposed to significant ashfall, leading to significant suspended solids in the water and occasionally lahar hazards, which are more threatening to the Agoyan HEP than direct ashfall (Appendix 1). Intake mechanisms such as wicket gates, turbine covers, and blades are particularly at risk of abrasion from the ash-laden water. Severe pitting and scouring of the metallic components (Figure 2.2) has accelerated their degradation and four turbines have been replaced in the last 21 years.

To reduce the impacts from the intake of highly turbid water, Agoyan has a specially designed floodgate system in place so that the intake flow can be diverted away from generation components and directly flushed out into the river (Figure 2.2, inset). When there is heavy rain, causing an increased risk of ash-laden floodwaters and lahars, the dam operators monitor water levels and turbidity, and activate the protective bypass system as required.

Ash-induced insulator flashover

At Futaleufu (HEP) dam, Argentina (86 km from Chaitén volcano), major faults (flashovers) occurred on circuit breaker columns at the facility's control station following 50-100 mm of very fine-grained (<0.1 mm diameter) rhyolitic ashfall from the 2008 Chaitén eruption (Wilson et al., 2012). Flashovers also occurred across HV insulators on the 240 kV transmissions lines adjacent to the station, following light rain (estimated at 2 mm/hour) on 6 May 2008. The intense heat and severity of the arc during flashovers caused several of the insulators to explode and their metal pins to fuse, requiring total replacement of the insulators.

Figure 2.2: A severely abraded turbine that was removed from service at the Agoyan hydroelectric power plant, which is sited 5 km east of Baños. Ash-laden water filtering through the turbines has necessitated the replacement of 4 turbines in 21 years. Bottom inset: The Agoyan Dam and its (orange) floodgates are designed to let highly turbid water bypass the turbines so as to avoid accelerated wear of generation components.

To avoid build-up from further ashfalls and wind remobilisation of ash deposits, insulators were cleaned at the powerhouse and on the incoming transmission lines every 10 days for several months. The fine-grained ash did not wash off easily having formed a cement-like paste following wetting and drying, even when high-pressure water blasters were used. Generation at the HEP dam was unaffected by the ashfall or ash-laden water and remained in-service for the duration the eruption. However, when adjacent transmission lines were disrupted due to ash-induced insulator flashover, generation ceased (Wilson et al., 2012).

Ash ingress

On the Caribbean island of Montserrat, intermittent ashfalls from Soufrière Hills volcano at the Montserrat Utilities Ltd. (MUL) generation yard (located

9 km northwest of the volcano) have to be regularly washed away with water to prevent ash ingress (e.g. via wind mobilization) into the diesel generators. Ashfall events occur more often in active phases of dome growth, of which there have been five since the onset of the eruption in 1995. Ash is carried to the west by the prevailing wind, but occasionally northwest to the inhabited areas, where it can affect the generation yard. Air intake filters are changed more frequently using high-pressure water blasters every day during and after ashfalls (Sword-Daniels, 2010).

Controlled shut-down

Following ashfall during the 2011 eruption of Shinmoe-dake, the Kyūshū Electric Power Company (KEPC) initiated a controlled shut-down of the Nojiri and the Mizonokuchi HEPs to avoid ash ingress into their turbines. KEPC initiated a mudflow (lahar) monitoring programme that culminated in a precautionary shut-down of these plants following heavy rainfall on 10 February. The shut-down effectively avoided ash impacts and the shut-down and restart procedures were carried out without problems.

2.3.1.2 Transmission and distribution system components

Ash-induced insulator flashover

The 1980 Mount St Helens eruptions deposited volcanic ash over much of northwestern USA, in particular Washington State. The Bonneville Power Administration (BPA) transmits bulk electrical energy across the Pacific Northwest and experienced several ash-related outages during the eruption. BPA reported that, by 28 May 1980 (10 days after the initial eruption) approximately 25 momentary and 25 sustained outages had been recorded (up to 7h 40m) mainly on 115 kV and lower voltage systems serving customer utilities (Blong, 1984). A summary of the flashover incidents reported by Nellis and Hendrix (1980) is provided in Table 2.2.

Table 2.2: Flashovers on the Bonneville Power Administration system following the 1980 Mount St Helens eruption.

Date of ash fallout	Date(s) of impact	Ash received (mm)	Line(s) (kV)	Explanation	Comments
18-May	18-25 May	≤12	≤500	Momentary outage on BPA's Lower Monumental-Hanford 500 kV line and numerous flashover-related outages reported by customer utilities.	Ash from the 18 May eruption fell dry and did not cause immediate issues. Flashovers occurred when 7-12 mm rain was received over the 1-week period following the initial 18 May fallout.
18-May	18-25 May	≤12	<115	Numerous outages mainly on 115 kV or lower voltage systems serving customer utilities.	Some incidents initiated by ash loading on trees which caused branches to make contact with energised lines.
25-May	26-May	≤12	500	Paul Allston 500 kV line trip-out due to suspected ash contamination.	Evidence of flashover across a jumper string found during a post 25 May survey.
25-May	27-May	6-9	69	Phase-to-phase (line to line) flashover between two 69 kV porcelain post-type insulators.	One insulator exploded from the flashover while the other insulator suffered severe burn marks from the arc.
25-May	2-Jun	≤12	500	Circuits on both Paul Allston 500 kV lines experienced flashover from suspected ash contamination.	Flashovers occurred during light rain.

Redoubt volcano, located on the west side of Cook Inlet in Alaska, erupted explosively on 20 separate occasions between December 1989 and April 1990 (Miller and Chouet, 1994). In December 1989, power outages resulting from insulator flashover occurred in the Twin City area, Kenai, after receiving ~ 6 mm of ash in conjunction with rain (Johnston, 1997a).

Falls of ash and mud from the Ruapehu eruption on 25 September 1995 caused flashovers on Transpower's HV (220 kV) lines located near the base of the volcano (~15 km from the vent). Approximately 3 mm of fine-grained (particles typically <250 μm diameter), wet ash coated the towers, conductors (220 kV), and glass insulators east (downwind) of the volcano (Transpower, 1995; Cronin et al., 2003). Strain insulators, which are oriented horizontally to anchor the ends of a line segment, flashed over. This caused voltage fluctuations and problems for electrical equipment throughout the North Island. For example, fluctuations in supply tripped the emergency power at Wellington Hospital causing non-essential supplies to be shed (Johnston et al., 2000). In addition, Transpower's automated reclose system, which recloses (reconnects) a circuit after a fault has occurred, had to be operated manually during the 1995–1996 eruptions because of the repeated ash-induced flashovers with every auto-reclose attempt (Wilson et al., 2009).

Following the May 2008 Chaitén eruption, a 68 km stretch of 33 kV line to Futaleufu township, Chile (75 km from the volcano) was coated with fine-grained (<0.1 mm particle diameter) rhyolitic ash of 20 mm to >300 mm in depth in some areas between 2-8 May 2008. Local linesmen reported that 10-20% of the ceramic insulators suffered flashovers after light misty rain between 6-9 May 2008. Following inspections, the lines company decided to replace all insulators on the affected stretch of line, as it was too laborious to clean or assess damage to each insulator. Many of the insulators that had suffered flashover were cracked and exhibited burn marks at the base where it screwed onto the supporting metal pin (Figure 2.3). Distribution transformers on the circuit were also reported to have suffered flashover damage.

Empresa Electrica de Guatemala (EEGSA) is a distribution supply (≤69 kV) company that provides electricity to three of Guatemala's 22 administrative departments. EEGSA reported numerous ash-related flashovers following the May 2010 eruption of Pacaya. Rain during the eruption added to the risk of ash contamination of HV equipment, and several faults (flashovers) occurred following 20-30 mm of coarse-grained ashfall in Guatemala City. Specifically, there were six 69 kV circuits that endured continual flashovers despite several attempts to re-close the circuits. Of these, Guadelupe lines 1, 2, and 3 were particularly problematic. On 28 May 2010 (the day after the eruption) a 25.88 MW load was shed from a 69 kV circuit causing a two-hour long outage (Appendix 2). Despite several reports of flashovers on the system, no burning or physical damage of transmission equipment was noted, thus no replacement or repair of equipment was required.

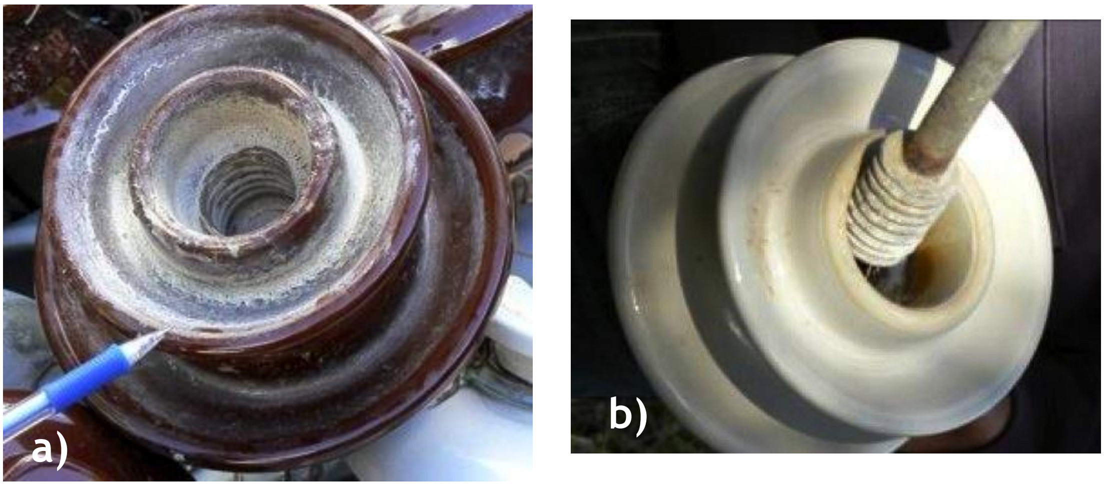

Figure 2.3: a) Fine grained ash adhered to the underside of a 33 kV porcelain insulator in Futaleufu, Chile following the 2008 Chaitén eruption. **b)** Underside of a 33 kV porcelain insulator that suffered ash-induced flashover following the 2008 Chaitén eruption. Note the brown burn mark (centre-right) from the high intensity arc during flashover.

Insulator tracking and corrosion

Leakage current or 'tracking' across contaminated HV insulators causes burning and etching of the insulator surface. This compromises the operational performance of an insulator and, in the case of composite polymers, can reduce the rate of hydrophobic (water repellent) recovery and therefore the dielectric (insulating) properties of the material (Gutman et al., 2011).

September 2009 to March 2010 was a period of particularly frequent ashfall in the inhabited northwestern areas of Montserrat from the current Soufrière Hills eruption. During this time a series of ashfalls caused flashovers, tracking, and burning of distribution equipment (e.g. insulators, surge arrestors, and bushings on pole-mounted transformers) throughout the villages closest to the volcano (Sword-Daniels, 2010). Remobilisation of the ash on Montserrat has also been a problem since the onset of the eruption in

1995, especially in and around the Belham Valley area. Tracking along insulators due to remobilised (and likely leached) deposits has also been observed, suggesting that epiclastic (reworked) ash may be sufficiently conductive to initiate flashovers and tracking possibly months after deposition.

Corrosion impacts are typically latent effects that are not noticed on Montserrat for several months after an ashfall. As of 2011, accelerated corrosion of transformer boxes at Isles Bay Hill (located approximately 5 km WNW from Soufrière Hills volcano) has required construction of additional wooden housing to shield the transformers from ash contamination (despite the transformers being designed to operate outdoors and withstand inclement weather conditions). When ash is very fine-grained (e.g. <0.1 mm particle diameter), it can penetrate the low voltage (e.g. <11 kV) ground and pole-mounted transformer boxes and is able to build up around the terminals. This has been known to cause the crutch (terminal) of the cables to burn out and/or deteriorate rapidly due to tracking across its surface.

During the January 2011 eruption of Shinmoe-dake, there were no reports of leakage current on KEPC's 66 kV or 6 kV distribution systems. However, the smaller 220 and 110 V distribution systems experienced some reports of leakage current and flashovers. KEPC reported that from the beginning of the eruption through to 24 May there were 54 public reports of corona discharge (electricity leakage with a characteristic crackling or arcing sound) and 29 public reports of flashover disruption of lines from the local transformer to the customer. The majority of these reported impacts occurred at connection points or where the line had been scratched or abraded on the insulator's jacket cover. Over half of the reports occurred between 7-10 February 2011 during a period of light misty rain.

Line breakage

Following a volcano-seismic crisis in 1983-1984, both Tavurvur and Vulcan volcanoes erupted on 19 September 1994, leaving much of the town of Rabaul (17,000 residents) covered in heavy ashfall, with 2-3 metres covering the southeastern suburbs (Blong and McKee, 1995; SMEC International 1999). PNG Power Ltd. (called PNG Electricity Commission (ELCOM) until 2002) is the primary generator and provider of electricity in Papua New Guinea. ELCOM's power supply was shut-down as a precaution at the start of the 1994 Rabaul eruption (Carlson, 1998). The Rabaul Power Station suffered little damage from ashfall, however, the station was decommissioned and the diesel generators removed due to the extensive damage to the surrounding areas (SMEC International, 1999). Falling trees and buildings damaged large sections of the distribution system, including some power transformers.

The same stretch of line that was affected by ash-induced flashovers between 2-8 May in Futaleufu, during the 2008 Chaitén eruption, was impacted again following heavy snowfall on 18 May 2008. The snow, together with the ash, on lines and poles created a significant load, causing lines to break and poles to collapse. The 6 mm lines were described as looking like '20 mm tubes' with the ash and snow accumulation. In addition, ash and snow laden branches collapsed onto lines resulting in further damage. In total, approximately 20 km of line and poles required replacement.

Controlled outage

Following contamination of Transpower's HV system during the 1995/96 Ruapehu eruption, affected circuits were de-energised and cleaning of 18 towers (and insulators) was undertaken on 27 September 1995 by four crews each consisting of four men (Transpower, 1995) (Figure 2.4). Three strings of insulators were found to have superficial damage (e.g. etching and burning) on their glazed surfaces as a result of flashovers. However, these insulators were not replaced, as, upon visual inspection, it was determined that they had not endured sufficient damage (e.g. cracking or puncturing of the discs) to affect their dielectric strength.

Approximately 50 mm of ashfall was received in Esquel, Argentina (110 km from the volcano) over the month of May following the 2008 Chaitén eruption. In this time the local municipal utility provider reported no damage to the four electricity distribution systems it manages: 132 kV, 33 kV, 220 V, and a three-phase 360 V. However, several shut-downs of the power supply were scheduled to allow cleaning of power transformers, after it was found that ash accumulation was creating the potential for flashovers.

2.3.1.3 Substations and switchyards

Ash-induced insulator flashover

Several EEGSA substations received >100 mm of coarse-grained (>1.5 mm particle diameter) ash fallout during the 27 May 2010 Pacaya eruption, particularly those substations located south of Guatemala City closest to the volcano. The EEGSA substations that received the most ashfall were scheduled for extensive offline cleaning on 29 - 30 May 2010. However, the arrival of tropical storm Agatha on 29 May 2010 hindered the cleaning procedure and large amounts of ash remained on substation equipment during the early hours of the storm. The combination of ash contamination, together with heavy rain from the storm, caused further faulting (flashovers) on the system, with several interruptions occurring throughout the event (Appendix 2).

With the passing of Agatha it was found that the rains had sufficiently cleaned all substation equipment and none but the Laguna substation (located ~5 km from the vent), which received >300 mm of lapilli-sized ash, required further cleaning. The power transformers were described by EEGSA staff as being the most problematic and difficult apparatus to wash free of ash because of the intricate array of cooling fins and sensitive components vulnerable to further damage from abrasion or water/ash ingress. As a preventive measure, ash was cleaned from transformer radiator fins to allow sufficient heat transfer and cooling of the apparatus.

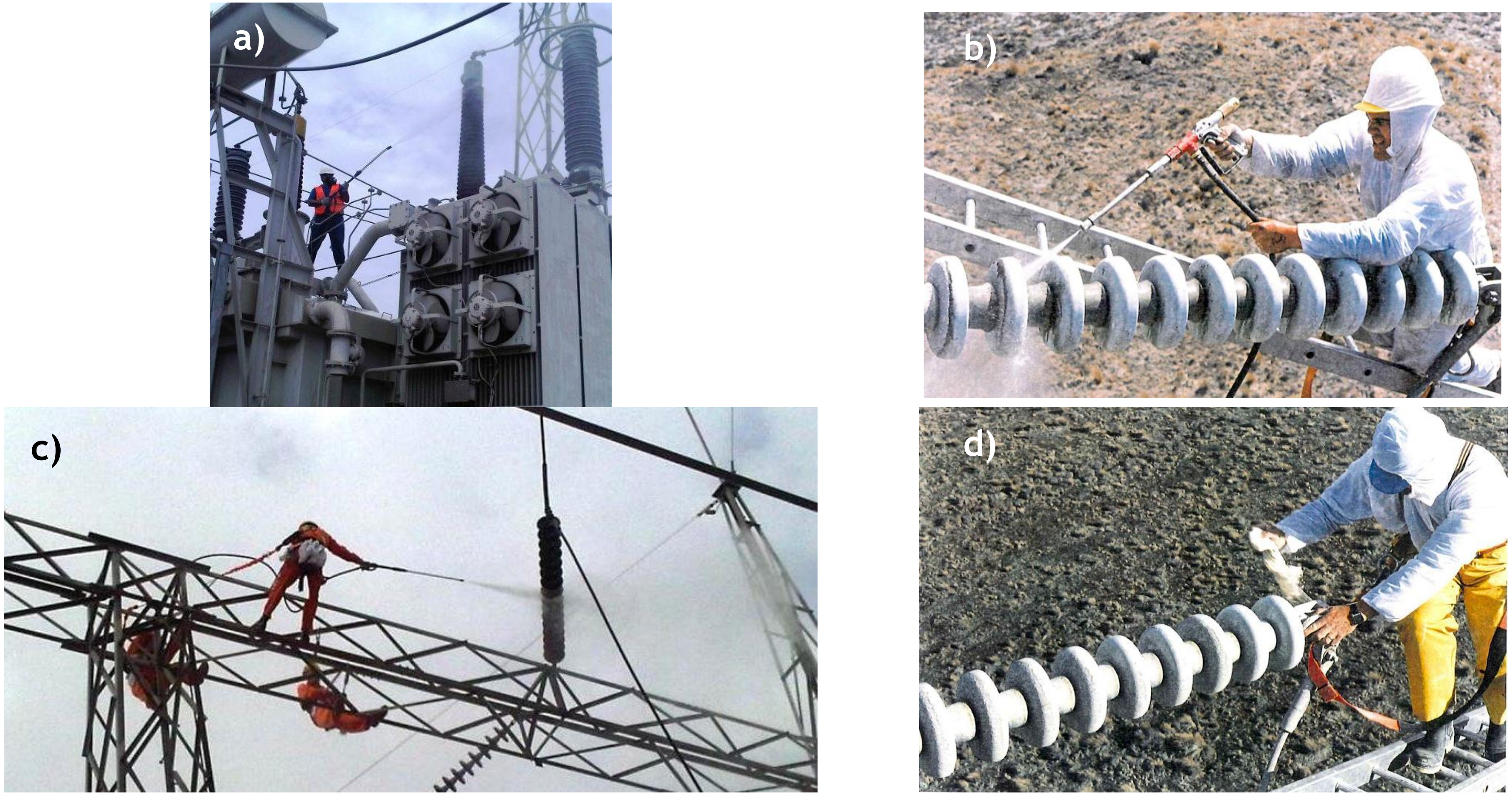

Figure 2.4: a) High-pressure de-energised washing of a power transformer bushing at a substation in Ecuador following the 2010 eruption of Tungurahua **b**) A linesman cleans ash from a de-energised 220 kV porcelain strain insulator located ~15 km from Ruapehu, New Zealand. **c)** Linesmen cleaning de-energised insulators at a Guayaquil, Ecuador substation after 1-2 mm of fine-grained ash fell following the 2010 Tungurahua eruption. **d)** Hand-cleaning ash from a de-energised 220 kV porcelain strain insulator after the 1995 Ruapehu eruption. Photo credits **a)** Transelectric, **b)** Transpower, **c)** Transelectric, **d)** Transpower.

Ash ingress

Transformer sheds within KEPC substations have open-veined windows that allowed ingress of ash to the buildings during the 2011 Shinmoe-dake eruption. Windows were blocked off at the time of the eruption, but the sheds became too hot several months later in summer, requiring filters to be fitted over the windows. At Miyazaki Power Centre, 48 windows required blocking and later filtering across 14 buildings. At Miyakonojo, 33 windows required blocking and later filtering across 10 buildings.

Decrease in resistivity of substation/switchyard gravel

In addition to transmission and distribution system components, ash from the 18 May 1980 Mount St Helens eruption covered surface rock in substation areas causing a major decrease in the ground resistance once wetted by rainfall. This had significant ramifications for step and touch potentials (voltages) present at affected BPA substations. Step potential is the difference in surface voltage between two points 1 meter apart (the step distance) under rated fault conditions, while the touch potential is the difference between the earthing grid voltage and the surface voltage at a point where someone standing on the surface can touch something that is bonded to the earthing grid. A decrease in resistivity of substation gravel means an increase in current passing through the body due to the step and touch potentials and a heightened risk of electrical shock or electrocution. This was identified as a serious danger for technicians entering the area and required de-energising and isolation of equipment before cleaning and/or repair (Buck and Connelly, 1980; Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Rogers, 1982).

Controlled outage

After each of the 1995/96 Ruapehu ashfalls, electricity generation, transmission, and distribution companies routinely cleaned ash from affected substations. On 17 June 1996, power supply was disrupted in parts of Rotorua city after a powerful flashover occurred across an 11 kV ground mounted distribution transformer bushing at a local substation, caused by ash and water contamination from a resident hosing ash from the roof of a neighbouring building (Johnston, 1997b). Thus, there was a focussed effort to make sure that all of the 11 kV bus-bars and insulators at substations were clear and free of any ash before power was restored (Bebbington et al., 2008).

Guatemala's Empresa de Transporte y Control de Energia Electrica (ETCEE) manages two large (230 kV) substations that were affected by the 2010 Pacaya eruption. These stations (Guate Sur and Guate Este) required offline cleaning shortly before the arrival of tropical storm Agatha. Cleaning involved the sweeping and brushing of ash from substation apparatus and surrounding yards. Substation equipment was subsequently washed using high-pressure water blasters.

The city of Guayaquil (Ecuador) received 1-2 mm of very fine-grained (<0.1 mm particle diameter) ash during the May 2010 eruption of Tungurahua, a rare event for the city. The ash fell during dry conditions and no instances of flashover were reported. As a precaution, however, substations critical to the continual supply of electricity to Guayaquil were cleaned to prevent ash-induced failure of HV equipment. To avoid permanent damage to the power transformers from overheating or ash-induced flashovers, each of the three transformer banks at the Pasquales substation had to be taken offline individually while associated sections of the yard were cleaned. The substation was re-energised once drying of substation equipment (following high pressure water washing) was complete. While remobilization of the ash was an inconvenience to substation workers for about a month following the initial ashfall, no further cleaning of equipment was required and no faults (unintended interruptions of supply) were reported (Appendix 1).

Ashfalls from the 2011 Shinmoe-dake eruption caused no direct impacts to KEPC's transmission lines or substations. However, on 1 February 2011, KEPC shut-down (de-energised) some transmission substations for cleaning. KEPC developed a special hot-stick (insulated pole, usually made of fibreglass) with a compressed air line attached for live-line (energised) cleaning of ash-contaminated equipment. A specially designed hot-stick connected to a high pressure water line was also developed (based on the design used for live-line cleaning of sea salt contamination) but due to the uncertain conductivity and therefore potential for flashover at the time, they took the precaution of only cleaning when de-energised. The Takaharu, Hirose, and Sadowara substations were de-energised while ash was wiped by hand from surfaces with a soft rag where practical and high-pressure water blasters were used to wash apparatus (e.g. power transformers, insulators, circuit breakers, arresters, bus bars, etc.). There was some benefit from rain cleaning, but rainfall intensities conducive to cleaning were unclear.

2.4 ANALYSIS OF IMPACTS

The generation, transmission and distribution, and substation components of a modern power system are vulnerable to different and specific ash-induced impacts depending on the equipment at each phase of power delivery. A summary of the ash impacts on the main components of modern power systems is illustrated in Figure 2.5.

We have chosen to use ash thickness as the most appropriate indicator of ash hazard intensity when analysing impacts to power systems. We selected it on the basis of its utility for gauging the accumulation of ash in the field (important for rapid damage assessment), its common use in ash dispersal models (e.g. Connor et al., 2001; Bonadonna et al., 2005), and its ease of application compared to other quantitative methods (e.g. the non-soluble deposit density, NSDD, a procedure used by electrical engineers (e.g. Sundararajan and Gorur, 1996)). Whilst there are limitations with this approach (e.g. grain size is a key control of ash adherence potential, composition is a key control on abrasion, soluble salt load and water holding capacity both influence conductivity, etc.), we found no other parameter was more suitable. Thus, the following section identifies the most vulnerable system components and, where possible, suggests critical ash thicknesses for each sector of the modern power system.

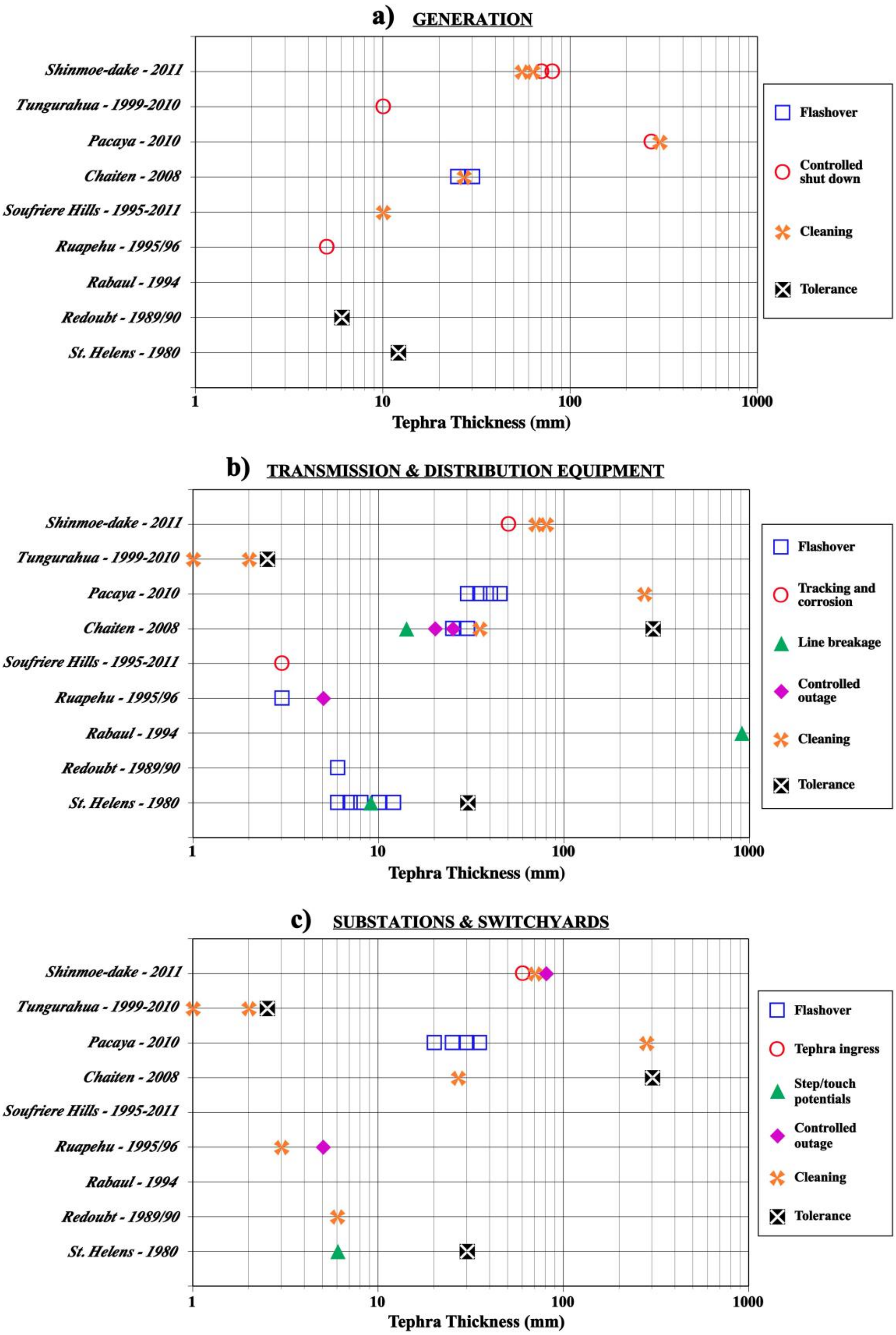

Figure 2.5: Summary of impacts and management approaches to the **a)** generation, **b)** transmission and distribution and **c)** substation and switchyard sectors of the case-study power systems following ashfalls. Ash-induced insulator flashover is the most common problem arising from contamination of power equipment and therefore poses the greatest threat to the reliability of power supply.

2.4.1 Generation

The most common disruptor of power at generation sites is controlled shut-down of HEP turbines to avoid accelerated wear of submerged components such as runner blades, labyrinth seals, wear rings, band seals, cheek plates, and wicket gates. Even HEPs designed to cope with large volumes of sediment, such as the Agoyan Dam in Ecuador, favour bypass of ash-laden waters over continued operation of the plant, which involves the risk of damaging their turbines.

Critical ash thicknesses for HEP sites are difficult to identify since every dam is designed differently and the exposure of each component to ash may not be the same as the nominal thickness. For example, turbines are exposed to suspended ash in the intake waters, the amount of which is a function of catchment size, flow rate, rainfall, etc., not just ash thickness experienced in a general area. In light of this, further research should focus on critical turbidity levels rather than ash thickness before shut-down of a generation facility must occur.

Insulator flashover at generation yards containing step-up transformers can cause cascading impacts, as was seen in Futaleufu, Argentina following the 2008 eruption of Chaitén. If power cannot be transmitted from a generation site due to contamination and subsequent flashover on transformation equipment (e.g. insulators and bushings) then the generated power cannot be transmitted to other sections of the system.

We are unaware of any direct ash impacts to thermal power plants. However, we highlight that ashfall is a hazard that could cause generation disruption or shut-down due to blockage of generator air intakes (e.g. as is avoided in Montserrat and was prevented in Japan following the 2011 Shinmoe-dake eruption) and off-site power resources (e.g. emergency lines or generators for back-up power). This is a significant knowledge gap that warrants further research. Similarly, some generation sites rely on HVA systems to keep sensitive electrical equipment at a maintained temperature (e.g. switching equipment and data centres). HVA systems are vulnerable to ash damage (e.g. abrasion of moving parts such as fans), corrosion, and arcing of internal electrical components, and air filter blockage, especially if air intakes are horizontal surfaces, although these impacts have not been recorded.

2.4.2 Transmission and distribution

According to our analysis, transmission and distribution systems are most vulnerable to insulator flashover from ash contamination. Insulator flashover can occur with ash thicknesses as thin as 3 mm (Ruapehu 1995/96) provided the ash is of sufficient conductivity. Additionally, if ash is not cleaned from insulators immediately following fallout then, with subsequent adsorption of moisture (e.g. mist, fog, light rain, etc.), ash will adhere strongly (i.e. cement) to all surfaces (making cleaning difficult) and cause latent effects such as corrosion and tracking (as experienced on Montserrat).

Line breakage due to ash loading was observed following several of the case study eruptions (Mount St Helens 1980, Rabaul 1994, and Chaiten 2008). Ash adherence to lines is highest during wet and freezing conditions, although this is a rarely observed impact (Figure 2.6b). Many power companies are liable for maintaining acceptable clearance distances between trees and power lines on both public and privately owned property. Provided these distances are maintained then the power system should undergo no issues with ash contamination of nearby vegetation.

2.4.3 Substations and switchyards

Immediate cleaning of substation equipment has been used as either a reactive or proactive measure against ash-induced flashover in several of the case studies presented (Mount St Helens 1980, Redoubt 1989, Ruapehu 1995/96, Tungurahua 2010, Shinmoe-dake 2011). Ash thicknesses received at substations during each of these eruptions have been wide-ranging (refer to Figure 2.6c), however, cleaning has commenced with ash deposits as thin as 1 mm (Guayaquil, Ecuador following the 2010 eruption of Tungurahua). In every instance where cleaning of substations has taken place, insulator flashover has been avoided and power companies have been successful in maintaining power supply. This highlights the critical importance of substations to the integrity of a power system.

No existing literature or research has documented impacts at switchyards. The lack of sensitive apparatus such as power transformers means that ash contamination at switchyards will have a lower probability of disrupting power supply. This suggests that switchyards are less vulnerable to ash-induced impacts than substations; however, more research is needed to verify this claim.

The only evidence of reduction in substation gravel resistivity comes from BPA reports following the 1980 Mount St Helens eruption. However, field data collected from CELEC EP (Ecuador) and EEGSA (Guatemala) suggest that replacement of contaminated substation gravel is not required so long as the ash and gravel mixture displays a resistivity value >3000 Ωm, as prescribed by IEEE Std 80 (2000).

2.4.4 Tolerance

Instances of tolerance to ash contamination have been noted in nearly every case study but are drastically under-reported. From the data it appears that many substation components mentioned in this chapter such as disconnect switches, bus bars, circuit breakers, capacitors, and metering transformers (voltage and current transformers used to monitor power quality) are less vulnerable to ashfall than other apparatus highlighted in this study (e.g. power transformers). However, the lack of data does not mean that these components are completely tolerant to ash-induced impacts but rather implies that further investigation is needed to quantify their vulnerability to ash hazards.

2.5 PROBABILISTIC ASSESSMENT OF INSULATOR FLASHOVER

Our review has shown that ash-induced insulator flashover can occur in all sections of a modern power system and is the most common impact from ash contamination. Factors contributing to ash-induced flashover are shown in Figure 2.6. Given the interdependencies between electrical, volcanological, and environmental factors that influence the likelihood of ash-induced insulator flashover, it is difficult to make a reliable prediction whether flashover will occur during a particular ashfall. However, from the case studies summarised here, simple probabilistic analysis can be undertaken to produce a function that estimates the likelihood of a flashover occurring causing system disruption.

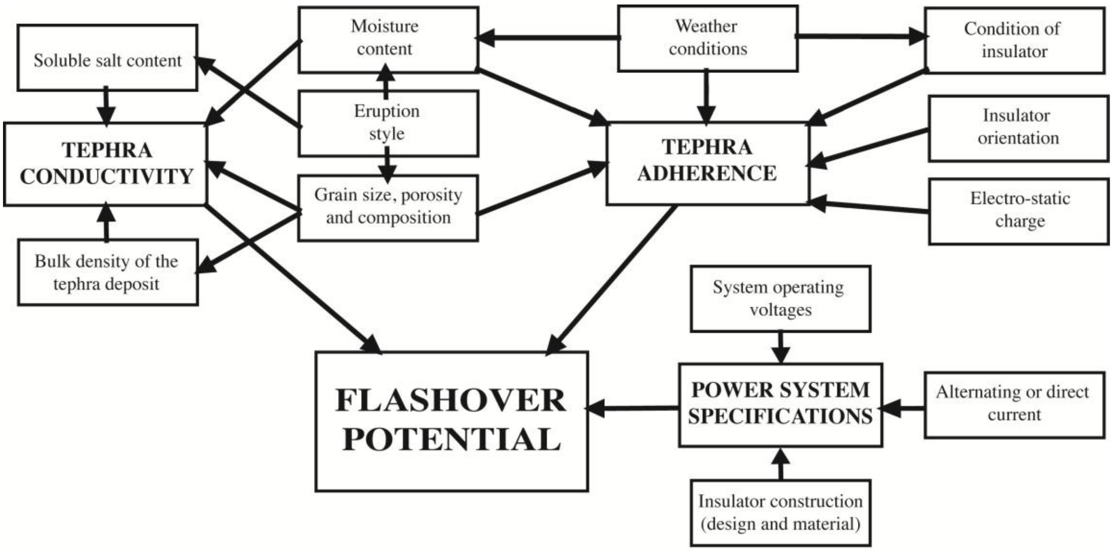

Figure 2.6: Flow chart illustrating the many variables influencing ash-induced insulator flashover (adapted from Johnston, 1997b).

We have used an event tree to conceptually illustrate the sequence of events required for ash-induced insulator flashover to occur (Figure 8). Each branch of the tree leads from a necessary prior event to a more specific outcome (e.g. from an eruption to an ashfall). Several of the events are controlled by external factors, such as conditions at the volcano (eruption style), environmental conditions (wind direction and precipitation), design of the power system, prior contamination of system components, etc. Such information requires input at the time of risk assessment for a particular scenario. However, considering the lack of quantified data for events 3-5 (Figure 2.7), our compiled review dataset of flashovers and tolerances allows us to create a fragility function that estimates the conditional probability of a flashover occurring for different ash thicknesses. This simple, first-order approach is designed to aid system operators in assessing the allowable accumulations of ash before initiating mitigation strategies.

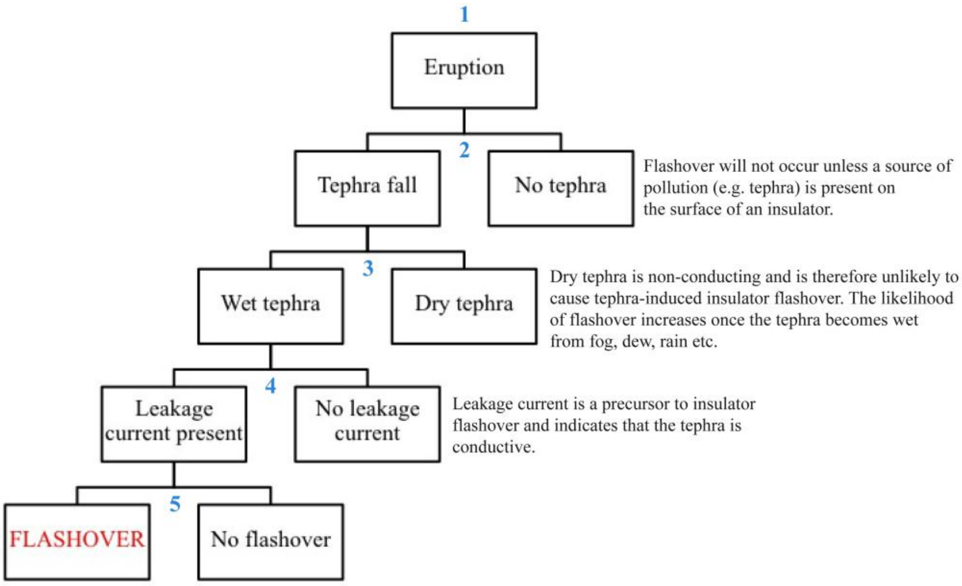

Figure 2.7: Event tree showing the sequence leading up to ash-induced flashover. At present, values for the likelihood of each event occurring at each node are not available to hazard managers or power system operators. The development of fragility functions will help to populate event trees such as this one with more robust data for interpretation.

In this instance, the limitations in the available data (discussed below) means we have chosen to only consider one type of impact (flashover across one cylindrical insulator or insulator string), the ash thickness at the time of flashover, and the presence of moisture in the ash upon flashover. By choosing to simplify in this manner, we focus only on the significant factors that dictate whether flashover will occur. However, this approach does not account for other influences such as detailed environmental conditions, prior contamination (e.g. salt spray), and insulator model, composition, and orientation as these are, in most cases, unknown.

2.5.1 Derivation of the fragility curve

Fragility functions give the conditional probability of exceeding a specific damage state as a function of the intensity of the hazard present (e.g. ash thickness). They are typically based on empirical observations of a particular system's or component's performance at varying levels of hazard intensity. For the purpose of this study, fragility functions can be defined as mathematical algorithms that relate the intensity of a hazard (e.g. ashfall) with a certain degree of loss or damage (e.g. 0-100%). Few studies in the field of volcanic hazards have utilised fragility functions, mainly due to the lack of quantitative damage or loss data. Limited examples include estimating the collapse probability of residential buildings from ash (e.g. Blong, 2003; Spence et al., 2005) and predicting building damage from pyroclastic flows (e.g. Baxter et al., 2005). While fragility functions have been used sparingly in probabilistic volcanic risk analysis, their usefulness has been demonstrated in other disciplines, notably in earthquake engineering to determine the probability of building failure at different ground shaking intensities (e.g. Rossetto and Elnashai, 2003; Akkar et al., 2005; Porter et al., 2007).

We can assume that because insulator flashover is a mutually exclusive event and HV insulators are designed to prevent the transfer of electricity from transmission and distribution equipment to earthed (bonded with the ground) apparatus, insulator flashover can be considered a 100% failure in performance. Conversely, instances of tolerance signify 0% failure (Figure 2.8).

As this is the first study of its kind to create a fragility function for HV insulators exposed to ashfall, and given our limited binary dataset, we have selected a logarithmic function to provide an estimate for the probability of flashover across a single cylindrical insulator or insulator string at different thicknesses of either wet or dry ash. After plotting the data, a line of best fit was applied and the resulting curves are presented in Figure 2.9. Results suggest that dry ash will not cause flashover but increasing thicknesses of wet ash on insulators will increase the likelihood of flashover. The generated curves and data trends agree with our observations from existing literature and experiences in the field.

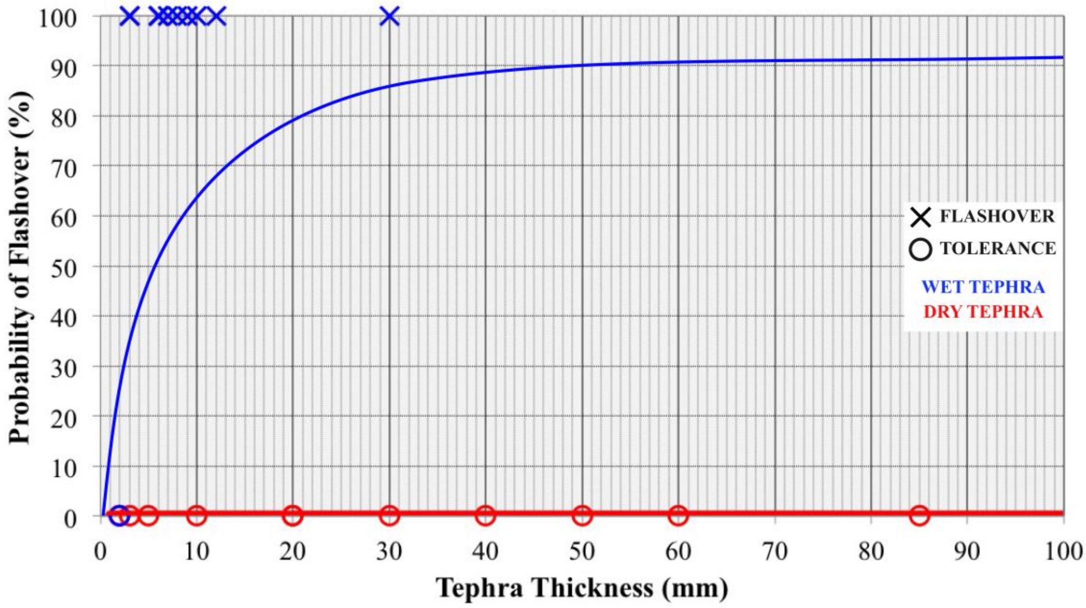

Figure 2.8: Logarithmic fragility curves showing the probability of ash induced flashover as a function of wet or dry ash thicknesses. Data are derived from systems that have either experienced flashover or exhibited tolerance to ashfall, or both. Insulator flashover is considered a 100% failure in performance while instances of tolerance signify 0% failure. However, these data have only been added to this Figure as a guide (i.e. they are not plotted); rather, the blue and red fragility curves (wet and dry ash, respectively) estimate the probability of flashover based on the discrete end member data points. Two anomalous wet samples at 2 and 300 mm (not shown) represent the only two *recorded* instances where wet ash did not cause insulator flashover.

There are limitations to this approach. Perhaps the most significant is the limited available dataset. Despite our best efforts, the field data do not acknowledge the many instances of tolerance on a power system during a single flashover event. For example, one insulator string may flashover while many dozens of strings that receive similar accumulations of ash elsewhere on the same circuit exhibit tolerance (do not fail). Furthermore, the data often do not indicate whether some of the flashovers occurred during the ashfall, or some time after the initial fallout (with subsequent rains or humid conditions). These are limitations of the retrospective, qualitative data collection methods employed. Nevertheless, the proposed model is intended to be a basic tool for volcanic risk assessment and serve as the basis for future analogue laboratory tests where more robust data can be collected to refine the model.

2.6 MITIGATION

Measures taken by power system operators in the aforementioned case studies to manage the risk of ash impacts have been largely reactive. That is, operators did not specifically strengthen or design their power systems to mitigate ashfall hazards. Throughout our research we found that system operators were largely unaware of the potential issues arising from ash contamination and, in many cases, were surprised at the onset of problems. Warnings from volcanic scientists were either unavailable or unheeded, creating a lack of situation awareness. This highlights the need for system protocols that emphasise partnership and knowledge transfer between volcanic scientists and system operators. With the start of ashfall, the majority of power system operators focussed on protecting the critical components of the system. It is clear from their actions that generation sites and substations are the most important nodes of a transmission and/or distribution system.

2.6.1 Mitigating the risk

Mitigation actions immediately prior to, during, and after ashfall have two basic purposes: (1) preventing or limiting ash entering systems or enclosures; and (2) effective and efficient removal of ash to prevent or reduce damage. Maintaining system infrastructure in a good state of repair and in clean condition is considered the best practise for long-term mitigation of ashfall hazards (Wilson et al., 2009).

There are four strategies to manage the risk of power system impacts from ashfall hazards (adapted from AS/NZS ISO-31000 (2009)):

1) Avoid the risk by deciding not to start/continue with the activity that gives rise to the risk.
2) Remove the risk source.
3) Change the likelihood.
4) Retain the risk by informed decision.

The following sections provide some key mitigation strategies according to each of the four risk management principles. In most cases, the suggestions addressed herein consider the range of known ash impacts and are based on our current knowledge. Ideally, they should be verified through trial before implementation. Further information on the application of these methods can be found in Table 2.3.

2.6.1.1 Avoiding the risk

De-energisation/shutting-down until ashfall has subsided

The most effective method of preventing ash-induced impacts is to avoid the risk altogether by shutting down, closing off and/or sealing off equipment until the ash is removed from the immediate environment. However, in many cases this is not practical or acceptable. For example, de-energising a critical substation (e.g. one that provides the only feed to an area) to possibly avoid several thousand dollars of damage to a particular piece of equipment may disrupt service resulting in losses of millions of dollars. Conversely, if a system operator chooses to retain supply during heavy ashfall and a power transformer suffers damage, then both service and component losses will be incurred. Thus, it can be safer to de-energise, clean contaminated apparatus and bear service losses than to continue operating with an unquantified risk. However, the decision to de-energise will also depend on the importance of the circuit(s) or apparatus in providing power to other critical infrastructure (e.g. emergency supply to nuclear facilities, other crucial nodes of the system, water supply, primary industry, etc.). In all instances, communication of decision making should be made to clients as rapidly and openly as possible to enable them to plan for disruptions.

The difficulty noted in making these decisions highlights the need for further quantification of system component vulnerability so that decisions made by system operators to mitigate ash impacts are effectively informed.

Land-use planning

Removing the risk source (the volcano) is not a feasible option. However, power companies can revise their land-use planning to re-route circuits and stations so that they do not lie proximal to or in the typical downwind path of a volcano. Whilst this is an extreme and potentially expensive measure, it is an effective one that has particular relevance for areas that endure frequent ashfalls such as those near Tungurahua or Soufrière Hills.

2.6.1.2 Removing the risk source

Live-line cleaning

Live-line maintenance is a method used by linesmen to clean and/or repair power lines without disrupting power to parts of the system and is an effective way to remove ash (the risk source) from power apparatus. No official cleaning guide or standard exists which outlines the most appropriate methods to clean ash from power system components, however, the methods employed by CELEC EP following the 2010 Tungurahua eruption or KEPC during the 2011 Shinmoe-dake eruption demonstrate the effectiveness of simple techniques and routine practises that can be easily adopted by any electricity company looking to mitigate ash-induced impacts at substations. For live-line cleaning, an appropriate procedure is as follows (refer to IEEE Std 957 (2005) for further information on safe and effective live-line cleaning practises):

1) All cleaning personnel should be required to wear a facemask and eye protection in addition to any personal protection equipment required by the power company;

2) Compressed air cleaning (with or without a non-abrasive component) can be used to remove initial large amounts (e.g. >3 mm) of ash. If using compressed air alone then a pressure of 210 kPa or less (≤30 psi) should be applied to avoid a sandblasting effect on glazed ceramic surfaces such as insulators and bushings and other sensitive equipment. Care should also be taken to avoid blowing ash into other parts of the substation or onto lines that have already been cleaned;

3) A set of insulated tools for wiping, brushing, and washing ash from energised equipment should be devised (e.g. as outlined in IEEE Std 957 (2005)).
    a. For example, hot-sticks (designed appropriately for the component's rated voltage) fitted with brush heads or rags (typically made of burlap) work well for 'hot-wiping' ash from substation equipment (e.g. insulators, bushings, switches, busbars, circuit breakers, etc.);

4) Depending on how strongly the ash has adhered to equipment, low, medium or high-pressure (e.g. 1,400 – 7,000 kPa) water blasting should be used to thoroughly rinse away any residual ash. If the ash has become heavily cemented to insulators then soft-media blasting may be an effective alternative (refer to Table 2.3 for more information);

5) A routine and continuous cleaning programme should be maintained until the threat of airborne ash contamination is over (including that of remobilised ash deposits).

Offline cleaning

For de-energised cleaning, the following procedure has been adapted from methods employed by Transpower (New Zealand), CELEC EP (Ecuador), and KEPC (Japan) and from those outlined in IEEE Std 957 (2005):

1) All substation equipment must be de-energised and earthed prior to cleaning;

2) All cleaning personnel should be required to wear a facemask and eye protection in addition to any personal protection equipment required by the power company;

3) Depending on the state of the ash (e.g. wet or dry) transformer bushings and radiator fins should be cleaned by hand using soft rags followed by high-pressure washing (see Figure 2.5a);

4) Insulators, bus bars, circuit breakers, metering transformers, and other critical apparatus should be cleaned by hand in a similar procedure as that used for transformers. Extra care should be taken to ensure that all surfaces are cleaned, including the undersides of insulators. Additional materials, such as wet or paraffin-soaked cloths, steel brushes, or steel wool, may be needed for insulators with strongly adhered ash deposits;

5) If ash deposits are strongly cemented to ceramic surfaces (insulators and bushings) then a mild (and inert) solvent or detergent (e.g. OMYA brand products) can be applied and wiped clean using soft brushes, rags, paper towels, or non-abrasive nylon pads. Steel wool can also be used when other cleaning tools are ineffective, however, caution should be exercised to avoid abrading ceramic surfaces and remove all metal particles left by the steel wool. No solvents should be applied to polymer insulators unless advised by the manufacturer.
6) CELEC EP noted that contacts on disconnect switches (electrodes) are especially difficult to clean and may require scrubbing with a rough sponge or nylon pad to remove the contact grease in which ash becomes embedded;

7) The substation can be re-energised once all substation equipment has been dried using soft rags.

The above methods can be easily adapted for transmission and distribution lines and insulators. Alternative cleaning methods for transmission and distribution system components (energised and de-energised) are provided in Table 2.3.

Table 2.3: A range of potential mitigation options against ashfall impacts based on the risk management principles outlined in AS/NZS ISO-31000 (2009)

RISK MANAGEMENT	MITIGATION OPTION	EXPLANATION		SOURCE
Avoid the risk	De-energise vulnerable circuit(s)	Shutting down generation facilities and substations until ashfall has subsided is the most effective method of prevention against ash-induced failure of power supply equipment.		
	Land-use planning	While removing the risk source is impossible in this case, power companies can revise their land-use planning and re-route their power system so that it avoids close proximity to volcanic hazards.		
Remove the risk source	Fixed spray nozzles	Spray nozzles fixed to structures so that insulators are periodically cleaned with water to remove ash before critical volumes can accumulate.		IEEE Std 957, 2005; Cakebread et al., 1978
	Offline (de-energised) cleaning	Cementation makes it increasingly difficult to clean power supply equipment, regardless of the technique employed. Therefore, controlled outage (offline) cleaning should take place before cementation occurs. This may be a particularly effective method for power companies located near volcanoes which exhibit prolonged activity such as Soufrière Hills, Montserrat (U.K.) and Tungurahua, Ecuador.		IEEE Std 957, 2005
	Live-line (hot) cleaning	Water blasting	Live-line cleaning using low (e.g. 1,000 to 2,100 kPa), medium (e.g. 2,100 to 2,750 kPa) or high-pressure (e.g. 2,750 to 7,000 kPa) water blasters has been an effective pollution removal practise since the earliest beginnings of electricity transmission.	Yasuda and Fujimura, 1976; IEEE Std 957, 2005
		CO_2 pellets	CO_2 (dry ice) pellets are a commonly used nonabrasive component for live-line cleaning. In the CO_2 cleaning process, the pellets of frozen CO_2 strike the surface of the insulator, penetrating through the adhered contamination layer to the insulator surface. The pellet then sublimates into a gas, which blasts the contaminant from the surface.	

		Soft-media blasting	Soft abrasive materials such as walnut shells and ground corncobs blasted onto the surface of energised ceramic insulators have been successful in removing strongly adhered pollution. These types of organic-blast media are sometimes mixed with a small fraction of limestone to improve performance.	
	Self-cleaning technology	Recent studies have investigated the potential of a self-cleaning insulator which utilizes an applied voltage to repel dry ash from its surface. Ash can be negatively or positively charged and, during the positive or negative half cycle of an AC waveform, the force of electrostatic repulsion is strong enough to repel ash particles so that the risk source is eliminated at an early stage.		Mee et al., 2012; Wightman and Bodger, 2011
Change the likelihood	System redundancy	Power systems are often designed to withstand the loss of any single component (e.g. a large power transformer). When a power system adopts this approach, it is said to be 'N-1 secure' because it can cope with losing any one of its N components and continue to carry the demand load. N-1 secure systems reduce the likelihood of ash-induced disruption of supply.		Berizzi et al., 2000
	Adding more insulators	A proven way to improve the contamination performance of an insulator string is to add more discs (units). This increases the creepage distance and therefore the flashover voltage of the insulator string. However, there are many limitations to this approach, as explained in IEEE Std 957 (2005).		Farzaneh and Chisholm, 2009
	Using insulators of appropriate design	There is a wide variety in the design of insulators used in the power delivery process. Depending on the climatic and pollution patterns at a given site, insulator materials (e.g. ceramic versus polymer) and profiles (e.g. standard versus aerodynamic or fog-type) should be carefully chosen to accommodate the local conditions.		IEEE Std 957, 2005; IEC 60815-1, 2, 3, 2008
	Resistive glaze insulators	Resistive glaze insulators are coated with a semi-conducting glaze which creates a continuous leakage current of between 0.7 to 1.0 mA. This leakage current causes the surface temperature of the insulator to rise slightly, thereby reducing condensation and wetting on the insulator's surface.		Al-Hamoudi, 1995
	Booster sheds	Booster sheds are used to increase the diameter of conventional glass and porcelain insulators or bushings and prevent the formation of continuous streams of water which might cause flashover during live-line washing or torrential rain. Booster sheds may be an effective measure against insulator flashover as they (1)		Ely et al., 1978; Wu et al., 1998; Filho et al., 2010

		act as a barrier to the propagation of discharges initiated during leakage current and (2) prevent the underside wetting of insulator sheds more effectively than standard insulator types.	
	Creepage extenders	Creepage extenders are an alternative to booster sheds and are designed to reduce the potential for pollution-induced flashover by increasing the creepage distance of post-type insulators (typically found at substations). This improves the electrical strength of the insulator, however, creepage extenders are most effectively applied on bushings and surge arrestors than post insulators.	Farzaneh and Chisholm, 2009
	RTV coatings	Room temperature vulcanising (RTV) coatings are a silicon-based application that is painted on the surface of HV insulators in heavily polluted areas to prevent pollution-induced flashover. The hydrophobic property of the coating causes moisture to bead on the insulator surface. The inability of water to form a continuous conductive film thus reduces the likelihood of leakage current initiation and subsequent flashover. Additionally, solid contaminants are engulfed by the mobile molecular structure of the silicone compound, creating a barrier between the pollutant (ash) and ambient moisture.	Kim et al., 1990; IEEE Std 957, 2005
Retain the risk by informed decision	Direct conductivity analysis	An alternative to the equivalent salt deposit density (ESDD) analysis, directly measuring the electrical conductivity of volcanic ash deposits may provide a more robust and rapid electrical characterisation of ash. Data acquired from ESDD and or conductivity measurements may have a practical use in tephra modelling and, when used in combination, this information could potentially alert system operators to the areas most vulnerable to high accumulations of ash and therefore those circuits with a high likelihood of ash-induced flashover.	
	Dust deposit gauge (DDG)	DDGs collect fresh and unaltered ash samples that can be used for electrical characterisation analysis (such as ESDD). If ash accumulation levels are gradual (e.g. <1 mm per week) then periodic collection and measurement of volume conductivity can support system operators in the decision to clean affected sections of the system.	Gutman et al., 2011; IEC 60815-1, 2, 3, 2008
	Dummy rig	A 'dummy' insulator string with a shorter creepage distance (and therefore lower flashover voltage) is installed and energised to the same potential as an adjacent line. Flashover of the dummy string will occur first and thereby warn operators of critical pollution levels.	IEC 60815-1, 2, 3, 2008

	Ultraviolet ray (UV) cameras	Partial discharges initiated during high amounts of leakage current cause the air around a polluted insulator to ionise. This ionisation process excites nitrogen molecules and creates the emission of ultraviolet radiation. UV cameras that have a built-in UV pulse rate counting feature have the potential to serve as a non-contact, quantitative indicator of leakage current pulse rate and intensity (the main precursor to flashover).	EPRI, 2002; Farzaneh and Chisholm, 2009
	Infrared (IR) cameras	Similar to UV cameras, infrared cameras have some ability to measure the pollution-induced leakage current. The heat produced from leakage current and dry-band arcing (discharges across dry zones created by the heat from continuous leakage current) can be intense enough to produce heat signatures which are detectable by IR technology.	Farzaneh and Chisholm, 2009
	Real-time pollution monitoring	Real-time monitoring of electrical parameters such as leakage current can help to identify critical contamination conditions. Measurements are taken directly from the problem area and the data are analysed remotely, where system operators can decide the appropriate counter-measure(s) to take.	Richards and Renowden, 1997; Lannes and Schneider, 1997
	Robotic monitoring and cleaning	Robotic monitoring and cleaning systems provide rapid analysis of polluted/damaged power system apparatus. The ability of a robot to govern itself via infrared and visual imaging presents a viable and safe option for preventing ash-induced flashover.	Wu et al., 2009

2.6.1.3 Changing the likelihood

System redundancy

The probability of two or more independent faults taking place on a power system simultaneously is very low (Berizzi et al., 2000). However, to account for this low risk (but high consequence) event, power systems are often designed to withstand loss of individual lines or elements such as power transformers. When a power system adopts this approach, it is said to be 'N-1 secure' because it can cope with losing any one of its N components and continue to carry the demand load. N-1 secure systems reduce the likelihood of ash-induced disruption to power supply, however, do not consider the far-reaching effects of ash that can cause numerous faults over hundreds of square kilometres of assets.

Insulator modification

HV insulators designed to operate in polluted conditions come in a range of different shapes and sizes and are constructed from several different materials (IEC-60815-1, 2, 3, 2008). Depending on the climatic and pollution patterns at a given site, insulator materials (e.g. ceramic versus polymer) and profiles (e.g. standard versus aerodynamic or fog-type) should be carefully chosen to accommodate the local conditions. Adapting the types of insulators used in volcano-proximal zones could reduce the likelihood of flashover, minimise the effects of tracking and leakage current, and ultimately improve system reliability.

A logical way to improve insulator contamination performance is to increase the number of insulators (or length of a single insulator) on a line or substation. Contamination flashover performance tends to scale linearly with creepage distance so adding three new discs to a string of ten identical ones can improve the flashover strength by 30% (Farzaneh and Chisholm, 2009). However, this approach is not without limitations, including a loss in acceptable line clearance distance and the difficulties in changing intricate types of insulators such as those found at substations.

2.6.1.4 Retaining the risk by informed decision

Doing 'nothing'

In the case of minor ashfalls, it may be more economical for power companies to retain the risk by leaving small deposits (e.g. ≤ 3mm) on insulators, lines, and structures to be cleaned naturally by rain and wind action. The informed decision to leave ash on power hardware should depend on the electrical conductivity of the ash, a factor that is largely influenced by the amount of ionic content in the form of soluble salts present on the ash particle's surface. In the case of substations, however, heightened attention to these facilities with only small accumulations of ash (e.g. 1 mm in the case of the 2010 Tungurahua eruption) suggests that immediate cleaning is essential to ensuring the safe and reliable provision of electricity to society.

Real-time pollution monitoring

Real time pollution monitoring can provide some indication of contaminated conditions on energised insulators. For example, analysis of leakage current and/or partial discharge on contaminated insulators can warn system operators of critical pollution levels prior to flashover (Farzaneh and Chisholm, 2009).

A rapid field method for measuring the resistivity (conductivity) of freshly fallen/falling ash in space and time would be a useful risk assessment tool for power system operators. For example, if conductivity values are known before substantial deposits of ash can accumulate (e.g. >1 mm) then ashfall forecasts can be combined to provide an early indication of which facilities and sections of lines may be at the greatest risk of impacts, such as insulator flashover.

Use of the fragility model to forecast flashover

When opting to retain the risk, there is significant uncertainty about failure thresholds. Our fragility model comprises impact data from various different eruptions and thus, a range of different ashfalls. The fragility function therefore accounts for the many variations in electrical conductivity (and therefore potential for flashover) present in each case-study ash. When used in combination with real-time pollution monitoring and an analysis of ash electrical properties, a more robust indicator of ash-induced flashover can be produced. The addition of near-real time information provided by volcanic scientists such as ashfall dispersal (isopach maps) and fall rates will further strengthen power system operator decision support.

2.6.2 Response plan

Heightened operational readiness, efficient monitoring, and impact assessment of any disruption or damage are key elements of good risk mitigation practise. Response plans should include procedures to monitor warnings from volcano observatories (including notification of eruptions and potential ashfalls), reducing or shutting down operations, and accelerated maintenance and ash clean-up operations, including access to filters and cleaning/disposal equipment.

Based on the lessons learned from our review, the following response plan will aid power system operators in preparing for and mitigating impacts from ashfall hazards:

1) Secure the health and safety of staff. Goggles and masks are essential for protection, but so are safe operating procedures, as horizontal surfaces (e.g. roads and ladders) can become very slippery;

2) System operators should maintain situation awareness by actively monitoring warnings and advice from local volcano observatories or relevant agencies to obtain the most up-to-date scientific alert levels, eruption warnings, ashfall maps, and forecasts. Operators should establish and maintain these connections during non-crisis periods;

3) Prepare a system for cleaning equipment before, during and after (e.g. for remobilised deposits) the event. This should include an estimate of the number of people and equipment required which can be predetermined by the magnitude of the ashfall. When problems

arise (e.g. notification of leakage current or corona discharge) a rapid response can be made;

4) Monitor the volcanological information from hazard scientists/agencies (e.g. ashfall forecasts, isopach maps, fall rates, etc.), the power dynamics of the system (e.g. voltage fluctuations, leakage current, etc.), and conductivity of the ash (by equivalent salt deposit density (ESDD) analysis or resistivity measurements). Based on these observations, make informed decisions on whether to continue supplying power to vulnerable sections of the system;

5) Implement a mitigation strategy (as detailed in Table 2.3) if the benefits of maintaining power supply outweigh the financial consequences of de-energising all or part of the system.

2.7 FUTURE DIRECTIONS

There is need for comprehensive standardised documentation of ash-induced impacts and cases where preventative measures have been employed and subsequent success in maintaining constant supply during and/or after a volcanic eruption has been achieved. Knowledge of ashfall impacts and mitigation is very limited, so any systematic assessment from technical experts is extremely valuable. In particular, it would be useful to know the percentage of adverse impact occurrence on the system as a whole. For example, in order to better define fragility functions, we must know what percentage of insulators flashover on a given stretch of line that receives similar thicknesses of ashfall. Identification of those components most often affected by ash contamination together with further development of cleaning and mitigation strategies will undoubtedly strengthen the resilience of electric power systems.

Further research is needed to design power systems that are resilient to ashfall hazards. Proactive and reactive response plans, cleaning methods, volcanic and electrical monitoring techniques, and mitigation strategies must be furthered and synthesised to provide adequate decision support for system operators. Additionally, ash samples intended for electrical analyses such as conductivity and ESDD should be collected from specific impact sites to ensure accurate representation of the electrical properties that have contributed to the impact. These are vital first steps in working towards providing reliable power supply to society during ashfalls.

2.8 CONCLUSIONS

We have identified the key sources of risk, areas of impacts, events and their causes, and their potential consequences for power systems exposed to volcanic ashfall. The following conclusions can be drawn from this study:

1) Case studies from around the world highlight the vulnerability of power systems to ashfall hazards and emphasise the need for more robust planning and mitigation strategies against ash contamination. Volcanic ash can disrupt power supply in the following ways:
    a. Ash-induced flashover on HV insulators or transformer bushings.
    b. Controlled outages for ash cleaning.
    c. Accelerated wear of HEP turbines (e.g. runner blades, labyrinth seals, wear rings, band seals, cheek plates, and wicket gates) and moving components at generation and substation facilities (e.g. transformer fans).
    d. Ash ingress into HVA systems which can block intakes causing reduction of functionality or failure of sensitive electronic equipment such as switching and data acquisition systems.
    e. Line breakage, bridged phases, and damage to towers and poles due to ash loading directly onto structures or by causing vegetation to fall onto lines.
    f. Deterioration of apparatus due to corrosion and degradation of insulators from burning and etching caused by ‘tracking’ and leakage current (initiated by conductive deposits of ash).

2) The most common cause of power generation, transmission, or distribution interruption arises from ash-induced insulator flashover. Dry ash will not cause flashover. Once the ash becomes wet, however, the likelihood of insulator flashover increases significantly, prompting immediate evasive action from power system operators.

3) We have developed a fragility function for estimating the probability of flashover across an insulator at a range of dry or wet ash thicknesses. Whilst it has a number of limitations, our model represents a first-order approach to probabilistically estimating the thickness of wet ash required to cause ash-induced insulator flashover.

4) We propose a number of untried but potential mitigation strategies to be used during and after an ashfall. The most effective mitigation strategy against ash impacts is shutting down substation and generation facilities until the ash has been effectively removed from the immediate area.
    a. There are no guidelines for cleaning ash from insulators or other exposed electrical infrastructure. This is a key knowledge gap.

5) Substations and generation sites have many critical components and, as a whole, represent microsystems within a larger power system. Future work should therefore look to quantify the vulnerability of all outdoor components involved in providing power supply to society.

6) Detailed and standardised reporting of power system failure and resiliency during or following ashfall is crucial to improving our understanding of the processes of ash-induced impacts and enhance the effectiveness of methods used within probabilistic volcanic risk assessment.

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Chapter 3: Investigating the electrical conductivity of volcanic ash and its effect on HV power systems

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The concept of the manuscript was developed through discussions between Mr. Wardman, Dr. Thomas Wilson, Prof. Pat Bodger and Prof. Jim Cole. Mr. Wardman devised the research objectives, conducted laboratory analysis, interpreted results and wrote the manuscript. Prof. Pat Bodger advised on trial design. Dr. Thomas Wilson made a significant contribution to refining and developing the manuscript. Prof. Pat Bodger, Prof. Jim Cole and Assoc. Prof. David Johnston carried out in-depth reviews of the manuscript by offering useful discussion of results and interpretations.

Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all.

The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work;
- In cases where the PhD candidate was the lead author of the co-authored work he or she wrote the text.

Name: *Thomas Wilson* Signature: Date: *28 March 2013*

Chapter 3

Investigating the Electrical Conductivity of Volcanic Ash and its Effect on HV Power Systems

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OVERVIEW

Minimal literature is available on the electrical properties of volcanic ash. This, together with the limitations of standardised contamination severity assessment techniques motivated the development of a new method to comprehensively account for the electrical, physical and chemical properties of volcanic ash promoting electrical conductivity. This chapter presents results from an electrical resistivity analysis of seven fresh ash samples and several ash proxies.

3.1 ABSTRACT

Volcanic ash contamination of high voltage (HV) power networks compromises the reliability of society's electricity supply. Ash-induced insulator flashover is a common problem on transmission networks during explosive eruptions, which is attributed to the high conductivity (σ) (low resistivity (ρ)) of volcanic ash. However, there have been few studies which have investigated the electrical conductivity of volcanic ash and how it may be influenced by different volcanological and environmental factors. In this study we have used a simple and rapid testing method to measure the influence of ash composition, grain size, soluble salt content, compaction and moisture (water) content on ash conductivity. We also developed physically, chemically and electrically equivalent ash proxies to be used for current and future laboratory experimentation. Results indicate that dry volcanic ash is non-conducting (ρ >1.56 x 10^7 Ωm), however, the conductivity of volcanic ash increases abruptly with the adsorption of water. Further increase in conductivity has been observed with increasing soluble salt content and compaction. All grain sizes (<32 μm to 1.4 mm) can exhibit high conductivity values (ρ <100 Ωm) and therefore have similar potential to cause flashover on HV insulators. The methodology development and results herein represent a benchmark for in-field testing during volcanic crises and for future studies.

3.2 INTRODUCTION

Society is critically dependent on a reliable supply of electricity to maintain economic activities and the health and safety of communities. As a result, consumers demand very high reliability from electricity networks, and electrical utility management organisations are commonly bound by legislative or consumer/contractual requirements to maintain operations during emergency events, including volcanic eruptions (Bebbington et al., 2008).

During an explosive volcanic eruption ash is injected into the atmosphere and distributed downwind of the volcano. Distribution of ash is controlled by eruption column height, particle size of the ash and climatic conditions (especially wind direction and strength and humidity) at the time of the eruption (Carey and Sparks, 1986). Even in small eruptions, thousands of square kilometres may be impacted by ashfalls (Johnston et al., 2000). This is an important consideration, with 9% of the world's population estimated to be living within 100 km of a historically active volcano (Horwell and Baxter, 2006). Although ashfalls rarely endanger human life directly, threats to public health, disruption to critical infrastructure services (e.g. electricity and water supplies, transport routes, waste water and communications), aviation, building damage and primary production, can lead to significant societal impacts (Horwell and Baxter, 2006; Stewart et al., 2006).

Previous studies have shown that volcanic ash can cause disruption to electricity supplies in the following ways (adapted from Wilson et al., 2009):

1) The accumulation of volcanic ash on HV (e.g. >33 kV) insulators can lead to flashover (the unintended electric discharge over or around an insulator (Figure 3.1)), which often leads to the disruption of service. When flashover occurs on external insulation (bushings) for power transformers, this can cause damage to the apparatus and will most certainly result in the disruption of power supply;
2) Line breakages and damage to towers and poles due to ash loading, both directly onto the structures and by causing vegetation to fall on to lines, particularly in heavy, fine ashfall events. Snow and ice accumulation on lines and overhanging vegetation will further exacerbate the risk;
3) Breakdown of substation and generation facility control equipment; such as air-conditioning/cooling systems due to ash penetration which can block air intakes and cause corrosion;
4) Controlled outages during cleaning.

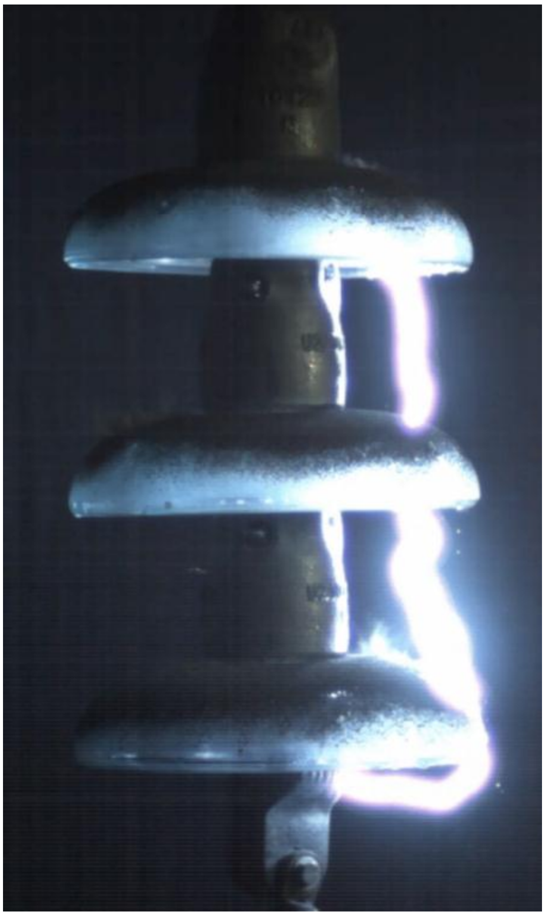


Figure 3.1: Insulator flashover across three glass 'fog-type' units (sheds) contaminated with ~2 mm of wet ash. Photo taken in the University of Canterbury HV laboratory.

Impacts to electrical networks following eight different eruptions have been summarised in Figure 3.2. For further information, refer to Wilson et al. (2009; 2012).

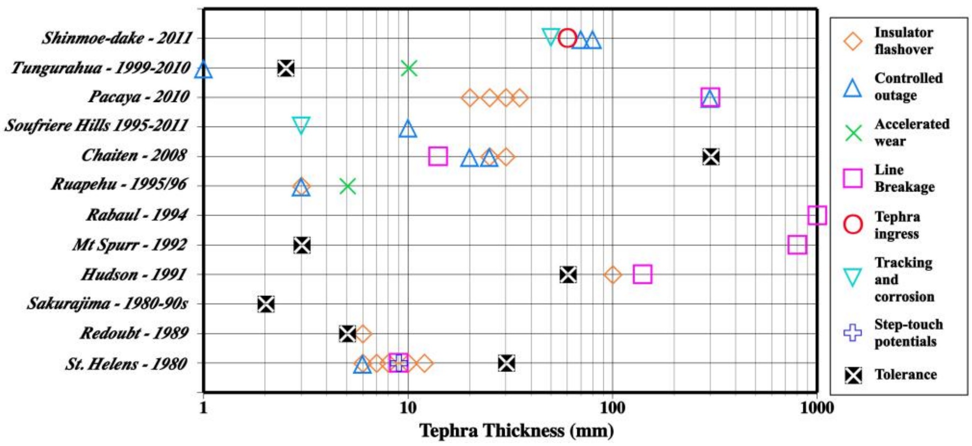


Figure 3.2: Impacts to HV transmission systems following volcanic ashfall events since 1980 (adapted from Chapter 2). The most common problem arising from volcanic ash contamination of HV equipment is insulator flashover.

Of these, the most common impact is insulator flashover. The purpose of HV insulators is to ensure the isolation of energised components (e.g. conductors/lines) from other transmission apparatus such as steel towers or wooden poles. When ash of sufficient electrical conductivity accumulates on (contaminates) an insulator it can generate an unintended electrical discharge which propagates itself around or across the surface of the insulator. This is known as a 'flashover'. Factors contributing to flashover are shown in Figure 3.3.

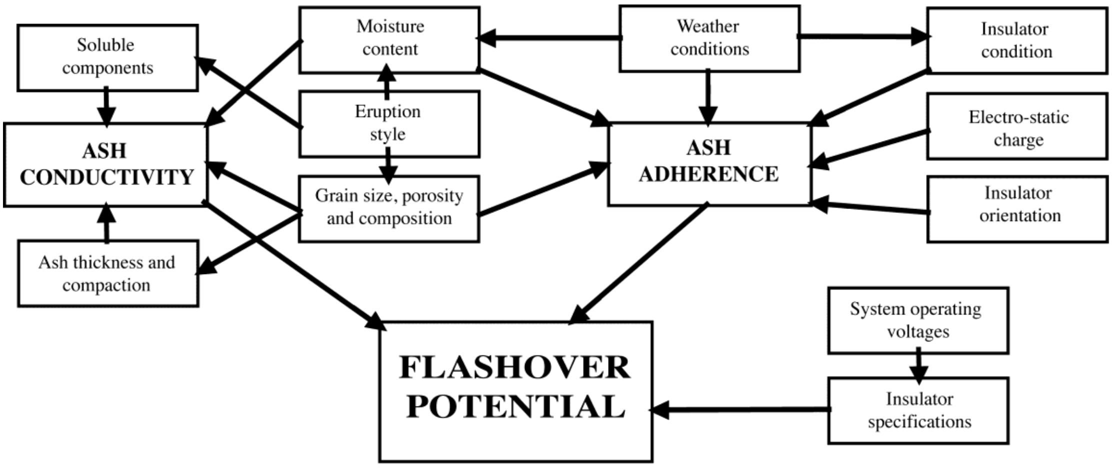


Figure 3.3: Flow chart diagram illustrating the many factors influencing insulator flashover (adapted from Johnston, 1997).

While ample anecdotal evidence exists of ash-induced flashovers (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Blong, 1984; Tuck et al., 1992; Blong and McKee, 1995; Johnston, 1997; Naranjo and Stern, 1998; Wilson et al., 2009), there is remarkably little empirical data available on the electrical properties of volcanic ash. This is somewhat surprising as it is a key factor in the disruption of electrical transmission systems after volcanic eruptions. Current understanding is limited to anecdotal information collected during volcanic impact reconnaissance trips (e.g. Wilson et al., 2009; Appendices 1 and 2) and investigations carried out by power utility companies in the wake of a volcanic eruption. A key study was by Nellis and Hendrix (1980) who performed an electrical analysis of the volcanic ash that fell on the Bonneville Power Administration transmission network following the 1980 Mount St Helens eruption (Washington, USA). This pioneering work, however, had a number of limitations, in that it only used one type of ash (1980 Mount St Helens) and did not consider how ash characteristics, such as grain size, grain morphology, soluble salt content and adherence characteristics, might affect conductivity.

This chapter presents a method for testing the electrical conductivity of ash and explore the influence that moisture (water) content, soluble salt content, grain size, compaction and composition have on conductivity. This will provide a better understanding of how different properties influence the conductivity of volcanic ash. Seven pristine ash samples are analysed. However, the logistical and practical difficulties of obtaining freshly fallen ash that has not been leached by rain means only limited types and volumes of ash are available for analysis by our research group. Therefore a pseudo (synthetic) ash has been developed which mimics the electrical properties of fresh ash, but can be manufactured to specific parameters to test different characteristics, such as grain size and soluble salt load. A secondary aim of developing the pseudo ash was to manufacture it in large volumes for use in future analogue laboratory tests which analyse the vulnerability of power systems to ash contamination.

3.2.1 Characteristics of volcanic ash

Volcanic ash is generated by a plethora of different processes (Dingwell et al., 2012) but most efficiently by explosive eruptions. The fragmentation of magma generates variously-sized particles (pyroclasts) which are released into the atmosphere. These particles may be crystallized lava, glass or crystal fragments. The types of minerals present in volcanic ash are dependent on the chemistry of the magma from which it was erupted, with the most explosive ash dispersing eruptions of high silica rhyolite (Heiken and Wohletz, 1985). Volcanic ash is hard (~5 on the Mohs hardness scale) and is often highly angular. This angularity, together with its hardness, makes volcanic ash very abrasive. When volcanic ash is being transported in the volcanic plume, complex chemical interactions occur between the ash and the magmatic gases leading to the formation of salts on the surface of ash particles. The fine-grained nature of volcanic ash makes it an excellent retainer of moisture and once the attached salts are dissolved into solution, the volcanic ash thus becomes conductive, making it a hazard to the power system.

It is widely accepted that during explosive eruptions volatiles adhere to ash particles during interaction within the volcanic plume (Taylor and Stoiber, 1973; Rose, 1977; Oskarsson, 1980; Smith et al., 1982; Witham et al., 2005). Mainly sulphur and halogen gases and associated cations are adsorbed onto ash surfaces and dry to become soluble salts. Recent studies suggest that the formation of soluble halide and sulphate salts is largely due to the acid-mediated dissolution of the ash's silicate glass and minerals and subsequent precipitation at the ash-liquid interface (Delmelle et al., 2007). This process leads to the formation of thin deposits of salts on the ash's surface.

According to Witham et al. (2005), the volatile element concentration adsorbed to the surface of volcanic ash particles is largely dependent on:

1) Ash composition;
2) Type of eruption;
3) Gas-pyroclast dispersion following fragmentation;
4) Gas and ash concentrations within the plume;
5) Particle size and surface area;
6) Particle geomorphology (e.g. porosity and texture);
7) Environmental conditions (e.g. wind and humidity);
8) Amount of hydrothermal interaction at the volcano.

The volume of soluble salts on ash is thought to be a key parameter controlling ash conductivity. When dry, volcanic ash is highly resistant to electrical current flow due to the crystalline-solid structure of the salts which act more as an insulator than a conductor (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Johnston, 1997; Bebbington et al., 2008). However, when moisture is added to the material, these salts dissolve, providing an ionic pathway for the free flow of electrons. Finer grained ash

(<0.5 mm) will have a larger surface area per-unit-volume, meaning more space is available for the adsorption of volatiles. This increase in soluble salt content is likely to result in higher conductivity values. Finer grain sizes are more likely to be transported further from the volcano and thus over larger areas, increasing their likelihood of being deposited on power equipment (Blong, 1984).

No prior study has analysed the influence of volcanic ash compaction on conductivity, however, similar studies of soil conductivity suggest that increased compaction in fine-grained (clayey) soils leads to an increase in their electrical conductivity (Rinaldi and Cuestas, 2002). Within weeks of deposition, volcanic ash may experience up to 50% compaction of its original volume due to gravitational settling, wetting and drying processes, rain beat compaction and vibrations (such as vehicle traffic) (Johnston, 1997; USGS, 2010). Compacting an ash deposit increases the number of contact points between grains which facilitates the flow of electrical current. Conversely, compacting an ash deposit reduces the pore space which inhibits the infiltration of moisture into the deposit. This, in turn, may reduce the volume of water available for to leach ions from the ash's surface which will affect the ionic strength (and thus conductivity) of the water. The lack of empirical evidence makes it unclear whether this has any significant influence on the conductivity of the deposit. This suggests that the compaction variable should be an important control whereby compacted ash layers will demonstrate different conductivity values than those of uncompacted deposits.

The conductivity of a solid material depends somewhat on temperature. In general, conductivity decreases with increasing temperature (Giancoli, 2000). At higher temperatures, atoms are moving more rapidly and are arranged in a less orderly fashion. These atoms are therefore more likely to interfere with the electron exchange required for current flow. The effect of temperature on the conductivity of volcanic ash is not investigated here, as industrial studies on soil resistivity reveal that temperature has a negligible influence (IEEE Std 80, 2000).

3.2.2 Equivalent salt deposit density

The few studies which have characterised volcanic ash electrically (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Matsuoka et al., 1995) have concentrated on the ash's equivalent salt deposit density (ESDD). This standard method deduces the equivalent amount of sodium chloride (NaCl) required to yield the same conductivity as the contaminant (volcanic ash in this case) when dissolved in the same volume of water. Table 3.1 shows the relationship between site severity description and the corresponding ESDD measurement.

Table 3.1: Site severity index for ESDD (after Karady and Farmer, 2007). Nellis and Hendrix (1981) reported that 3-6 mm of Mount St Helens ash exhibited ESDD levels between 0.3-0.6 mg/cm^2, suggesting that volcanic ash has a very high contamination severity (and therefore a high potential to cause flashover on HV insulators).

ESDD (mg/cm^2)	Pollution Severity
0-0.03	Very Light
0.03-0.06	Light
0.06-0.1	Moderate
>0.1	Heavy

The ESDD analysis is typically used in the power transmission sector to determine when it is appropriate to commence cleaning of electrical lines and insulators in heavily polluted industrial areas. For example, in Malaysia, insulator cleaning generally occurs when ESDD levels rise above 0.03 mg/cm^2 (Ahmad et al., 2004).

Nellis and Hendrix (1980) used the ESDD approach to evaluate the severity of contamination on insulators which were affected by flashover after being covered by ash during the 1980 Mount St Helens eruption. Their study revealed that 3-6 mm of volcanic ash has a pollution severity of between 0.3-0.6 mg/cm^2, suggesting that the Mount St Helens ash had a high potential of causing pollution-induced flashover on HV transmission hardware (Table 3.1).

While the ESDD method is an appropriate measure of the soluble salt content of volcanic ash, it does not consider factors such as ash grain morphology, ash composition, chemical composition of attached soluble salts, and bulk density. This limits the value of ESDD analysis when attempting to better understand which ash characteristics influence conductivity and creates the need for a testing regime capable of accounting for all influences on the conductivity of volcanic ash.

3.3 SAMPLES

3.3.1 Fresh ash samples

Seven pristine volcanic ashes were used in this study. The volcano, eruption dates and compositional information are listed in Table 3.2. All ashes were stored in dry conditions within sealed polyethylene bags since collection. Non-essential movement was minimised to reduce modification of ash properties.

Freshly fallen volcanic ash loses its soluble content rapidly in the presence of moisture (such as rain or wet soil) so the collection of fresh volcanic ash must be done shortly after an eruption and adequately stored to avoid leaching of the soluble content. The low frequency of explosive eruptions and logistical difficulties of collecting pristine volcanic ashes meant we only had access to seven ashes (Table 3.2) collected following seven different eruptions. Whilst useful to establish the electrical properties of these particular ashes, it does not allow in-depth analysis of the influence of different grain sizes, soluble salt loads, soluble salt chemistries, bulk densities and grain morphologies which can vary significantly between and within explosive eruptions, on the electrical properties of the ash. It was therefore necessary to develop a pseudo ash which replicates the physical, chemical and electrical properties of freshly fallen volcanic ash, but could be manufactured to specific parameters.

Table 3.2: Sources of the seven fresh ash samples used in this study. Samples were obtained from a variety of locations and cover a vast time range. Additionally, four different ash compositions were tested during the resistivity analysis.

Sample ID	Volcano	Country	Duration of Eruption	Date of Collection	# Days Between Deposition and Sampling	Approx. Distance From Source (km)	Magma Composition
GRIM-11	Grímsvötn	Iceland	May-11	22-May-11	1	95	Basalt
EYJA-10	Eyjafjallajökull	Iceland	Apr-Oct 2010	15-Apr-10	<1	60	Trachyandesite
SHIL-09	Soufriere Hills	Montserrat (UK)	Jul 1995-Present	27-Nov-09	<1	7	Andesite
RDBT-09	Redoubt	USA.	Mar-Jul 2009	4-Apr-09	<1	110	Andesite
CHTN-08	Chaiten	Chile	May 2008-Present	28-May-08	6	90	Rhyolite
MRPI-06	Merapi	Indonesia	Apr-Jun 2006	27-Jun-06	5	5	Andesite
RUAP-96	Ruapehu	New Zealand	Sep 1995-Jun 1996	18-Jun-96	1	105	Basaltic-andesite

3.3.2 Pseudo Ash Samples

The replication of both soluble and non-soluble pollution for experimental use in the electrical industry is not uncommon. Kaolin, tonoko and bentonite (among others) have frequently been used in HV insulator contamination testing (e.g. Diesendorf and Parnell, 1974; IEEE Working Group, 1979; IEC 60507, 1991; Sundhar, 1994; Hernandez-Corona et al., 1999; Bennoch et al., 2002; Naderian et al., 2004; Gautum et al., 2006).

Unweathered Stoddart olivine basalt (from Halswell Quarry, Lyttelton volcano, New Zealand) (Guard, 1999) and rhyolite Kaharoa tephra (from the 1314 AD eruption of Tarawera volcano, New Zealand) (Nairn et al., 2004) were used in the creation of proxy ashes. Whole rock chemistry is provided in Table 3.3. Their low and high silica (SiO_2) compositions allowed a simple comparison of whether base rock chemistry influences conductivity. Bulk samples were crushed using a hydraulic press and subsequently milled with a ring pulveriser.

In order to investigate the influence of grain size on conductivity, eight pseudo ashes of different grain size were created. These were created by dry sieving the original crushed and pulverised product. Five grain sizes, <0.032, <0.1, <0.5, <1, and <1.4 mm, were produced to replicate ash deposits with wide particle size distributions. In order to analyse the influence of specific particle size fractions on ash conductivity, three pseudo ashes were sieved to 0.1<x<0.5, 0.5<x<1, and 1<x<1.4 mm.

To replicate the interactions at the ash-gas interface and other processes occurring between ash and volatiles within a volcanic plume, a simplified method of chemical dosing was used to produce soluble salts on the surfaces of the pseudo ash. Either sulphuric acid (H_2SO_4) or common salt solution (NaCl) was added to the pseudo ash to replicate the volatiles found on fresh ash. These compounds were chosen because of their high abundance during explosive volcanic eruptions (Rose, 1977; Delmelle et al., 2005; Witham et al., 2005; Delmelle et al., 2007). Approximately 15 cm^3 (~20 g) of dry ash was placed in a 30 cm^3 plastic vessel. Once the solutions had been prepared to their respective molar concentrations, 5 ml of H_2SO_4 or NaCl solution was added to each vessel and subsequently stirred to ensure even distribution of the solution throughout the ash. Vessels were then placed in an oven at 85 °C for a period of two days to evaporate the water from the slurry and expedite the formation of soluble salts. After one day of drying, a hard crust developed on the ash. To continue the drying process, it was necessary to gently break up and mix this crust using a plastic spatula to allow underlying moisture to evaporate.

Table 3.3: Whole rock chemistry for the Kaharoa tephra rhyolite (Nairn et al., 2004) and the Stoddart olivine basalt (Guard,1999). Given the different constituents minerals present in both pseudo ash rock types, we were interested to see whether whole rock chemistry would influence ash resistivity.

		Kaharoa rhyolite	Stoddart olivine basalt
Wt.%	SiO_2	77.89	47.75
	TiO_2	0.1	2.31
	Al_2O_3	12.56	14.78
	Fe_2O_3	1.04	12.28
	MnO	0.06	0.16
	MgO	0.07	7.36
	CaO	0.71	10.32
	Na_2O	3.73	3.12
	K_2O	3.82	1.16
	P_2O_5	0.002	0.56
ppm	V	4	207
	Cr	<3	255
	Ni	<3	124
	Zn	29	95
	Zr	89	187
	Nb	7	58
	Ba	941	417
	La	25	19
	Ce	54	62
	Nd	<10	28
	Ga	11	20
	Pb	16	3
	Rb	125	30
	Sr	50	610
	Th	12	4
	Y	29	26

A range of H_2SO_4 and NaCl molar concentrations were used, as it was unclear how much would be absorbed by the ash, react with the ash surface, or evaporate during the drying process. For the moisture content analysis, molar strengths 0.02, 0.18, 0.46, 1.81 and 9.19 M of both, NaCl and H_2SO_4, were prepared for the ash dosing procedure. Early results obtained from ash dosed with these solutions suggested that molar strengths >0.46 M were excessively high, thus the resistivity analysis employs concentrations no greater than 0.46 M. Table 3.4 shows the volumes and pH levels of the prepared dosing agents relative to their molar concentrations.

Table 3.4: Volumes, Wt.% and pH levels of the prepared dosing agents relative to their molar concentrations. The maximum molarity used during the resistivity analysis was 0.46 M while the resistance measurements taken during the moisture content analysis employed concentrations up to 9.19 M.

	Volumes	Wt.%	Molarity (M)	pH
	0.20 ml H_2SO_4 + 199.8 ml H_2O	0.1	0.02	1.74
	2 ml H_2SO_4 + 198 ml H_2O	1.0	0.18	0.74
H_2SO_4	5 ml H_2SO_4 + 195 ml H_2O	2.5	0.46	0.34
	19.70 ml H_2SO_4 + 180.3 ml H_2O	9.9	1.81	-0.26
	100 ml H_2SO_4 + 100 ml H_2O	50	9.19	-0.96
	0.21 g NaCl + 200 ml H_2O	0.1	0.02	7
	2.15 g NaCl + 200 ml H_2O	1.1	0.18	7
NaCl	5.38 g NaCl + 200 ml H_2O	2.7	0.46	7
	21.16 g NaCl + 200 ml H_2O	10.6	1.81	7
	107.41 g NaCl + 200 ml H_2O	53.7	9.19	7

In order to evaluate a more chemically complex acid dosing solution, waters from the crater lakes of Mt Ruapehu (central vent; pH 1.12) and White Island (pH -0.37) were also used. These waters have been enriched with soluble products from the active hydrothermal systems of each volcano and contain common volcanogenic elements which might be expected to leach from fresh volcanic ash (Table 3.5).

Table 3.5: Chemistry analysis of White Island and Ruapehu crater lake waters. When added to a pseudo ash, the diversity of anions and cations present in crater lake waters may provide a more realistic simulation of the ash-liquid interface within a volcanic plume.

	Ruapehu	White Island
Collection Date	June/2010	November/2009
Collection Temp. (°C)	31.9	56.5
pH	1.12	-0.37
Na (mg/L)	652	16878
K (mg/L)	96	3433
Ca (mg/L)	888	4121
Mg (mg/L)	1044	6631
Al (mg/L)	367	4830
Fe (mg/L)	413	7598
Cl (mg/L)	5527	97374
SO4 (mg/L)	7945	24789
F (mg/L)	134	897
Li (mg/L)	0.81	28
B (mg/L)	17.5	143
H2S (mg/L)	1.3	0.03
Br (mg/L)	10	221
NH3 (mg/L)	17.7	124

3.4 METHODS

3.4.1 Electrical resistance and resistivity

This study required a method capable of determining the electrical conductivity or resistivity of volcanic ash. Resistivity is the parameter derived from resistance measurements of materials, particularly with reference to HV systems.

Electrical resistance is defined as the measure of opposition to a flow of steady electric current by a material. Derived from Ohm's law, the electrical resistance of a conductor is:

$$R = \rho(l/A) \qquad (3.1)$$

where:

R is the electrical resistance of the test sample (measured in ohms, Ω);

ρ is the static resistivity (measured in ohms per metre, Ωm);

l is the distance between electrodes (measured in metres, m);

A is the cross-sectional area of the test sample (measured in square metres, m^2);

To better evaluate the electrical properties of volcanic ash, resistivity calculations, which are volumetrically independent, provide insight into the electrical behaviour of the material in bulk. Rewriting the resistance equation gives the resistivity:

$$\rho = R(A/l) \qquad (3.2)$$

Electrical resistivity can also be defined as the reciprocal of the conductivity (σ) of a material, typically measured in Siemens per metre (Sm) and expressed as:

$$\sigma = 1/\rho \qquad (3.3)$$

Conductivity is preferred when referring to the chemical composition of a material, whereas resistivity is preferred when recording electrical values. Given our interest in the ionic content of volcanic ash (attached solubles) and considering the standard electrical practise of primarily measuring resistivity to calculate conductivity, it is therefore appropriate to use resistivity and conductivity interchangeably.

As an example, if the measured resistance (R) of a volcanic ash sample is 5000 Ω, its cross sectional area (A) is 0.0036 m^2 (0.02 m x 0.018 m) and the distance between electrodes (l) is 0.015 m then following Equation 3.2, the resistivity of the ash sample is 120 Ωm and the conductivity is 8.3 x 10^{-3} Sm.

The resistivity of volcanic ash is measured under varying levels of moisture, soluble salt load, grain size and compaction. Because of the large number of variables involved in this study, each parameter that is likely to influence the resistivity of volcanic ash has been studied individually while the interdependencies are discussed in detail.

The electrical industry is required to provide safe working conditions for substation workers by making sure that surface gravel exhibits a resistivity >3,000 Ωm (IEEE Std 80, 2000). Following the 1980 Mount St Helens eruption, Buck and Connelly (1980) tested the resistivity of substation surface rock contaminated with volcanic ash using large scale apparatus to find that ash contamination significantly reduced the resistivity of switchyard gravel to 80 Ωm in the worst case scenario. We developed a resistivity analysis based on this procedure that follows the same electrical principles, but at a much smaller scale which is better suited for our experiments, given the limited amount of fresh ash available to us.

We modified the approach of Buck and Connelly (1980) to include two electrical monitoring instruments for measuring the resistance of volcanic ash samples. A high voltage (1 kV DC) Megger with an output range from 0.01 to 999 Megohms was used to take the extremely high resistance measurements of dry ash. A low voltage (1 V AC rms, 50 Hz) RCL (Resistance (R), Capacitance (C), Induction (L)) meter was used to collect more accurate data once resistance readings fell below 10,000 Ω. A resistance-measuring device consisting of vials housing two electrodes was manufactured to contain the ash samples and carry out the electrical readings (Figure 3.4). The electrodes or connection points consisted of two 2 x 1.8 cm rectangular aluminium plates, separated by a distance 1.5 cm apart and fastened into a fibreglass housing. The vials were fabricated specifically for these experiments as they provided an adequate and secure space to contain the ash and minimised the potential for sample losses during the testing procedure. The same volume of ash (5.4×10^{-6} m^3) was added to the vial with each experiment.

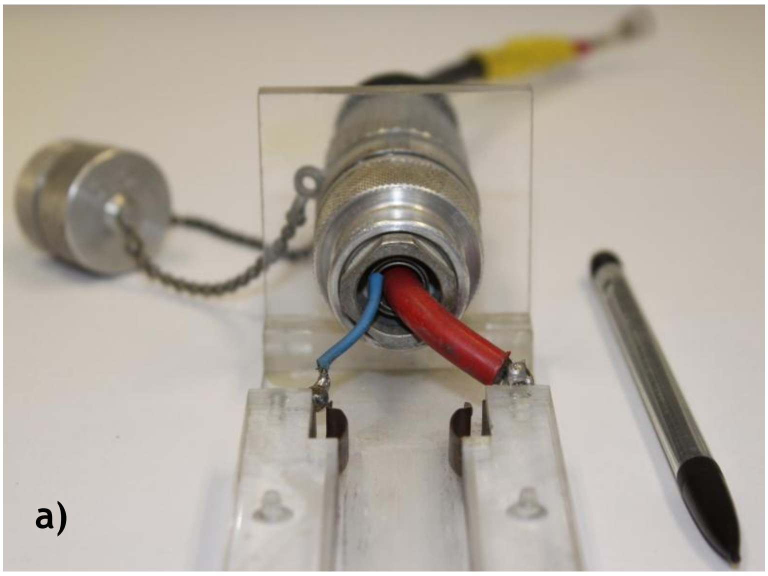


Figure 3.4: a) Electrode dock without vial showing the copper electrodes that make contact with aluminium plates on the testing vial. Plate dimensions on the vial are 2 x 1.5 x 1.8 cm (5.4 cm^3). **b)** Electrode dock with vial ready for testing. A Megger or RCL meter is connected to the wire terminals and a voltage is transmitted to the copper electrodes.

3.4.2 Parameters influencing resistivity

3.4.2.1 Moisture

Short supply of the RDBT-09 sample meant the influence of moisture content on the electrical resistivity of volcanic ash could only be tested on six of the seven fresh ash samples (GRIM-11, EYJA-10, SHIL-09, CHTN-08, MRPI-06, and RUAP-96). Only five of the eight pseudo ash grain sizes (<0.1, <0.5, <1, 0.1<x<0.5, and 0.5<x<1 mm) were tested during moisture content experiments. Due to the importance of maintaining a constant ionic content in ash samples, de-ionised water was used to treat the samples as well as to clean vials and tools after use. Approximately 0.5 ml of de-ionised water was incrementally added three times using a 5 ml pipette. The resistance of the ash samples was measured following each addition of moisture.

When adding water to each ash sample within the testing vial, it was difficult to ensure a homogeneous mixture. Thus, mixing was carried out using a plastic stirring needle until moisture was distributed throughout the bulk of the sample. As the bulk densities of the pseudo ashes varied based on their composition and grain size, three additions of water were found to be an appropriate maximum so as to not over saturate the samples. Mass was recorded for (1) the initial dry mass, (2) mass after adding initial moisture, (3) mass after stirring to account for ash lost by means of adherence to the stirring needle, (4) mass after second water addition, (5) mass after stirring, and (6) mass after third water addition. These values were necessary for the calculation of density and moisture content used later in the resistivity testing analysis.

Volumetric changes were not considered while moisture was added to both pseudo and fresh ash samples. Thus, resistivity values were not calculated and so resistance values are provided for analysis of the moisture parameter. Furthermore, compaction was not applied during this cycle of experiments. Hence, resistance values for the moisture content experiments are representative of uncompacted deposits of volcanic ash.

3.4.2.2 Soluble salts

To test for the presence of soluble salts on fresh ash, we leached soluble material from RUAP-96 (as this was the most plentiful ash sample) and then placed the leached ash through the resistivity analysis. 5.4 x 10^{-6} m^3 of RUAP-96 was added to a 100 ml vial. RUAP-96 was the only ash tested because it was the only fresh ash sample large enough to accommodate multiple tests. An arbitrary ratio of 1:10 ash:de-ionised water was mixed in a rotating agitator for a discretionary 24 hours to simulate natural leaching of any soluble content on the ash sample. After the 24-hour period, the water was tested for its conductivity using a Eutech Cyberscan PC300 conductivity meter and the values were compared with previous results for de-ionised water. The leached ash was then removed from the vial, placed onto filter paper and left in the oven at 85 °C until it had dried completely. The leached ash was then removed from the oven and placed through the resistivity analysis for further comparison against unaltered RUAP-96.

3.4.2.3 Compaction

To examine the influence of compaction on resistivity, a simple compaction test was devised. Pseudo and fresh ashes were placed in the testing vials in a dry state without applying any compaction and the electrical resistance measured. A 4.5 kg (~10 lbs) weight was then placed on top of a compaction tool for 3 seconds to compress the dry ash to between 80-95% of its original volume, and the electrical resistance measured. This is consistent with a lower limit on how much pyroclastic deposits compact in the field (up to 50% (Johnston, 1997; USGS, 2010). Volumes and bulk densities were calculated for the dry uncompacted (loose) and compacted scenarios.

To analyse the combined influences of moisture addition and compaction, a further experiment was conducted on pseudo and fresh ashes where approximately 0.5 ml of deionised water was added to each sample and subsequently weighed to calculate the moisture content. The water and ash were then mixed with a stirring needle to homogenize the sample before testing for the uncompacted resistance of the mixture. Compaction was again applied to the moistened sample to measure its compacted resistance value at 70-80% of its uncompacted volume. Electrical resistance readings were taken for the compacted samples and compared to uncompacted values. Changes in ash volumes were recorded for both uncompacted and compacted scenarios to assist with later calculations of resistivity and bulk density.

3.4.2.4 Grain size distributions

To analyse the influence of grain size on the electrical resistivity of volcanic ash, grain size distributions for all ash samples (fresh and pseudo) were determined using a HORIBA Partica LA-950 laser diffraction particle size analyser. Each fresh or pseudo ash was sampled two or three times and underwent a minimum of five analytical runs in the particle size analyser to ensure repeatability of the results. The output values were averaged and then plotted graphically to show the distribution curves (Figure 3.5).

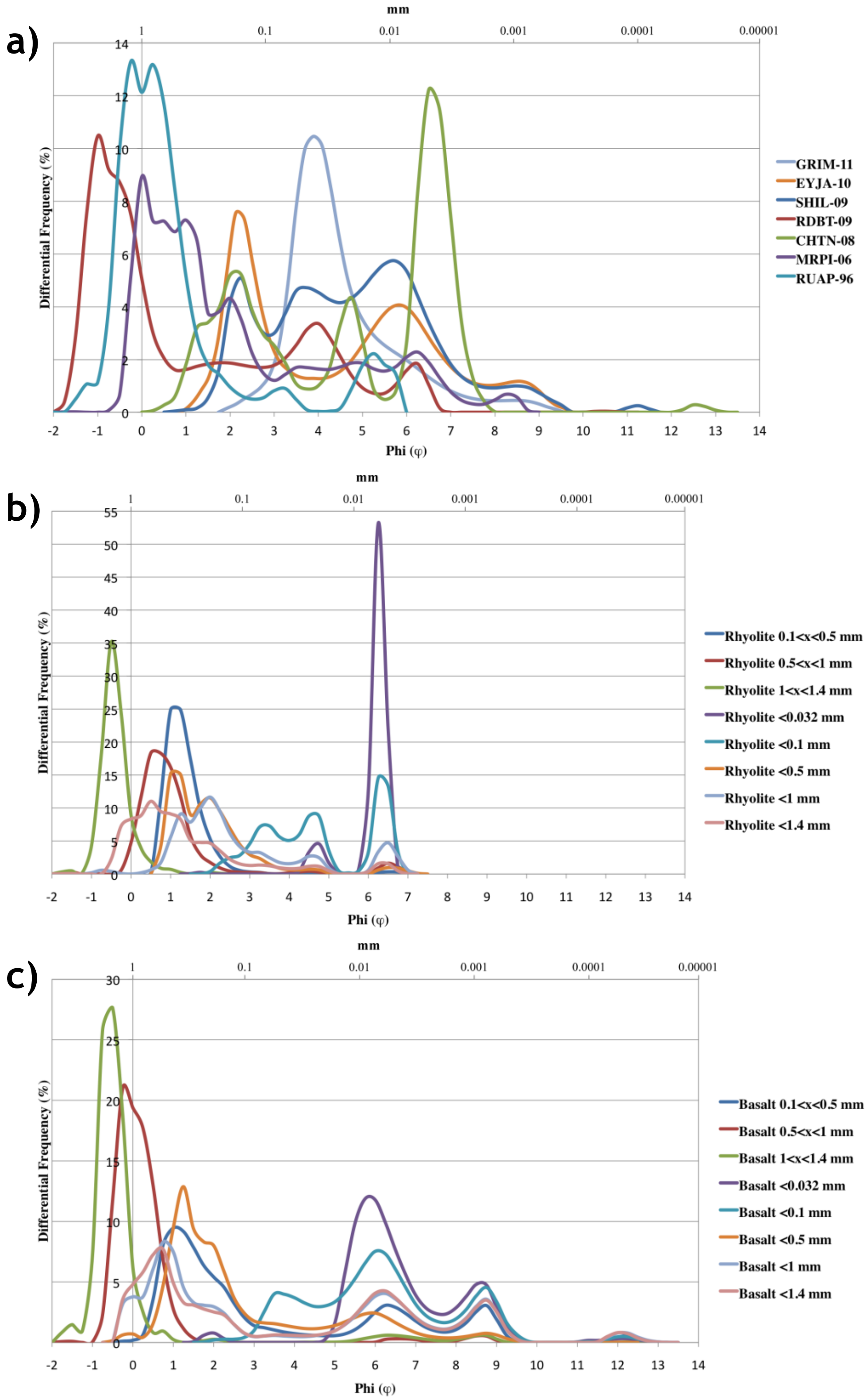


Figure 3.5: Grain size distributions for **a)** Fresh ash samples, **b)** Pseudo rhyolite and **c)** Pseudo basalt. Note the higher proportion of fines seen in the pseudo basalt.

3.5 RESULTS AND DISCUSSION

3.5.1 Moisture content

It has been suggested that volcanic ash becomes conductive only when wet (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981). The average of the resistance values for the six dry volcanic ash samples tested during the moisture content experiments was $6.64 \times 10^8\ \Omega$. This is an extremely high value and confirms the inability of dry volcanic ash to facilitate the flow of electrical current. With the first addition of water (Ave. 3.34 Wt.%), however, the fresh ash samples displayed a decrease in electrical resistance by several orders of magnitude (Ave. ρ = 279,045 Ω) and with each subsequent addition of water there was a corresponding further decrease in the ash's resistance (Figure 3.6). After the second and third additions of water (Ave. 6.51 and 9.92 Wt.%), the average of the resistance values for the fresh ash samples was 79,941 and 30,493 Ω, respectively.

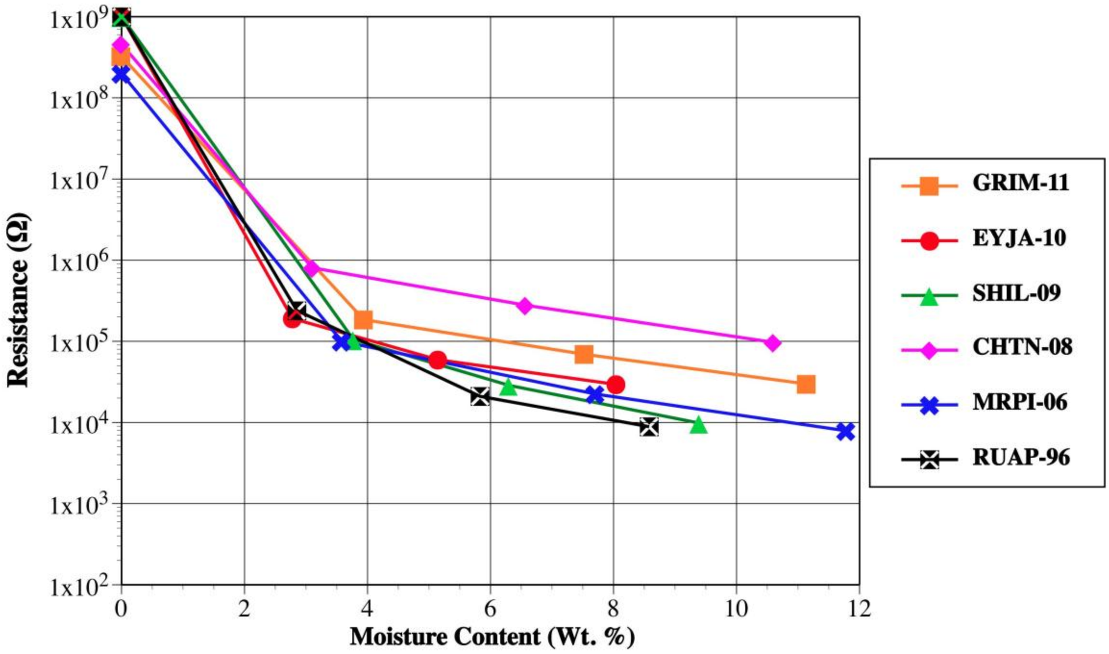
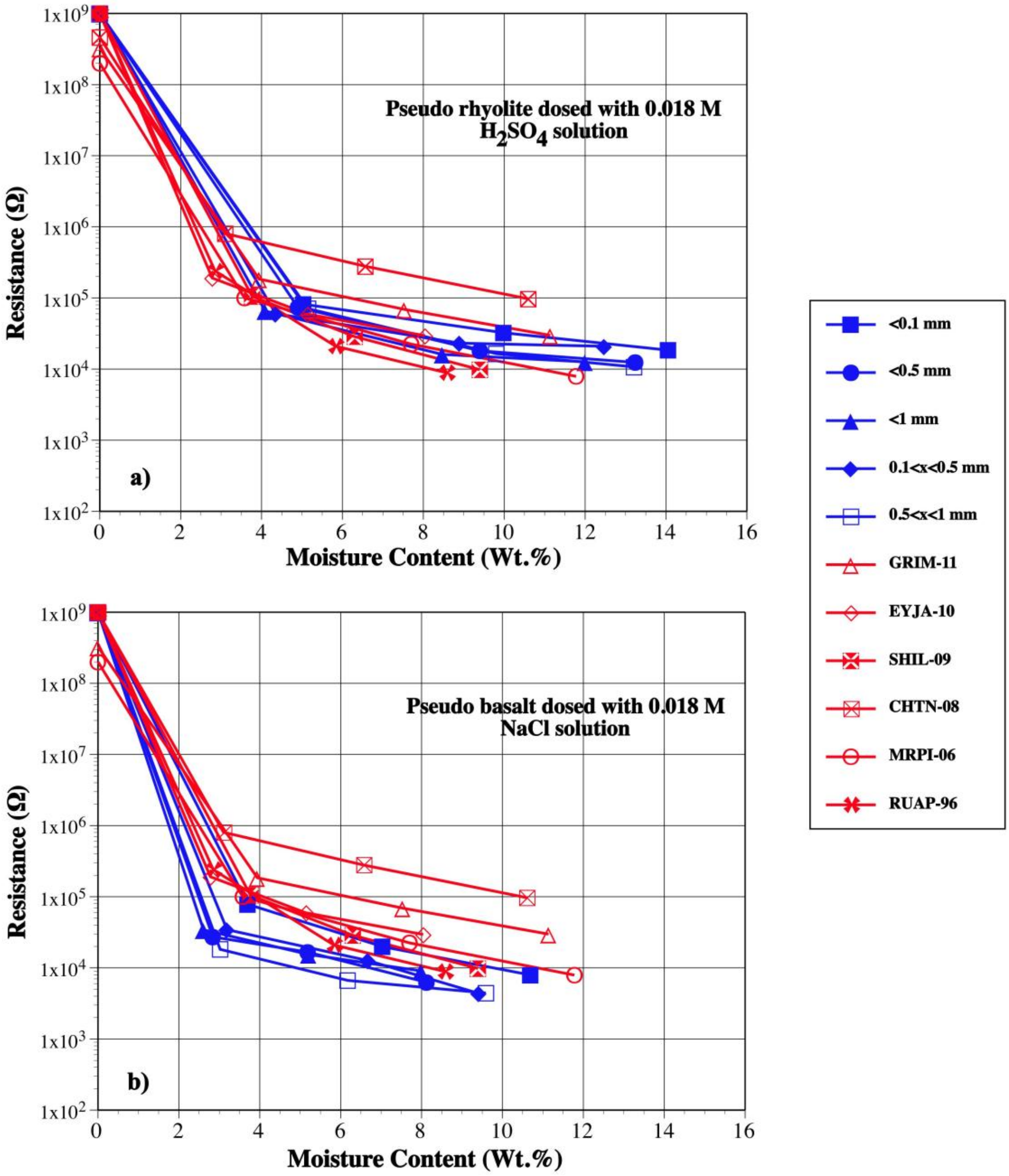


Figure 3.6: Resistance values for six of the seven fresh ash samples showing a general decrease in resistance with increasing moisture content (Wt.%). All ash samples show a similar trend of reduction in electrical resistance with increasing moisture content. However, CHTN-08 stands out as being the most resistant which is likely due to leaching of the sample before analysis.

High resistance values obtained for CHTN-08 had a large effect on the average of fresh ash resistance values. Not including CHTN-08, average moisture content becomes 9.1% and average fresh ash resistance drops to 8,866 Ω. This suggests that the CHTN-08 ash either (1) was partially leached after deposition and before collection or (2) the dome collapse from which this sample was collected did not release large amounts of gas with the event and therefore large volumes of soluble minerals did not form on the ash surface during gas/aerosol-ash interaction.

The average dry resistance value for pseudo basalt was 9.99×10^8 Ω while pseudo rhyolite displayed an average dry resistance of 5.41×10^8 Ω. These resistance values are not low enough for the transmission of significant electrical current. As with fresh ash, results from the pseudo ash moisture tests suggest that the electrical resistance is most affected upon the first adsorption of water (Figure 3.7).

Both the fresh and pseudo ash data supports the observations from past investigations (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981) which suggest that dry volcanic ash is effectively inert and non-conducting until moisture (water) is added and renders the deposit conductive. In the case of the uncompacted ash layers, increasing moisture content results in a decrease of electrical resistance. This resistance is further lowered with increasing soluble salt content and compaction.


Pseudo rhyolite dosed with 0.018 M H_2SO_4 solution
a)
Resistance (Ω)
Moisture Content (Wt.%)
Pseudo basalt dosed with 0.018 M NaCl solution
b)
<0.1 mm
<0.5 mm
<1 mm
0.1<x<0.5 mm
0.5<x<1 mm
GRIM-11
EYJA-10
SHIL-09
CHTN-08
MRPI-06
RUAP-96

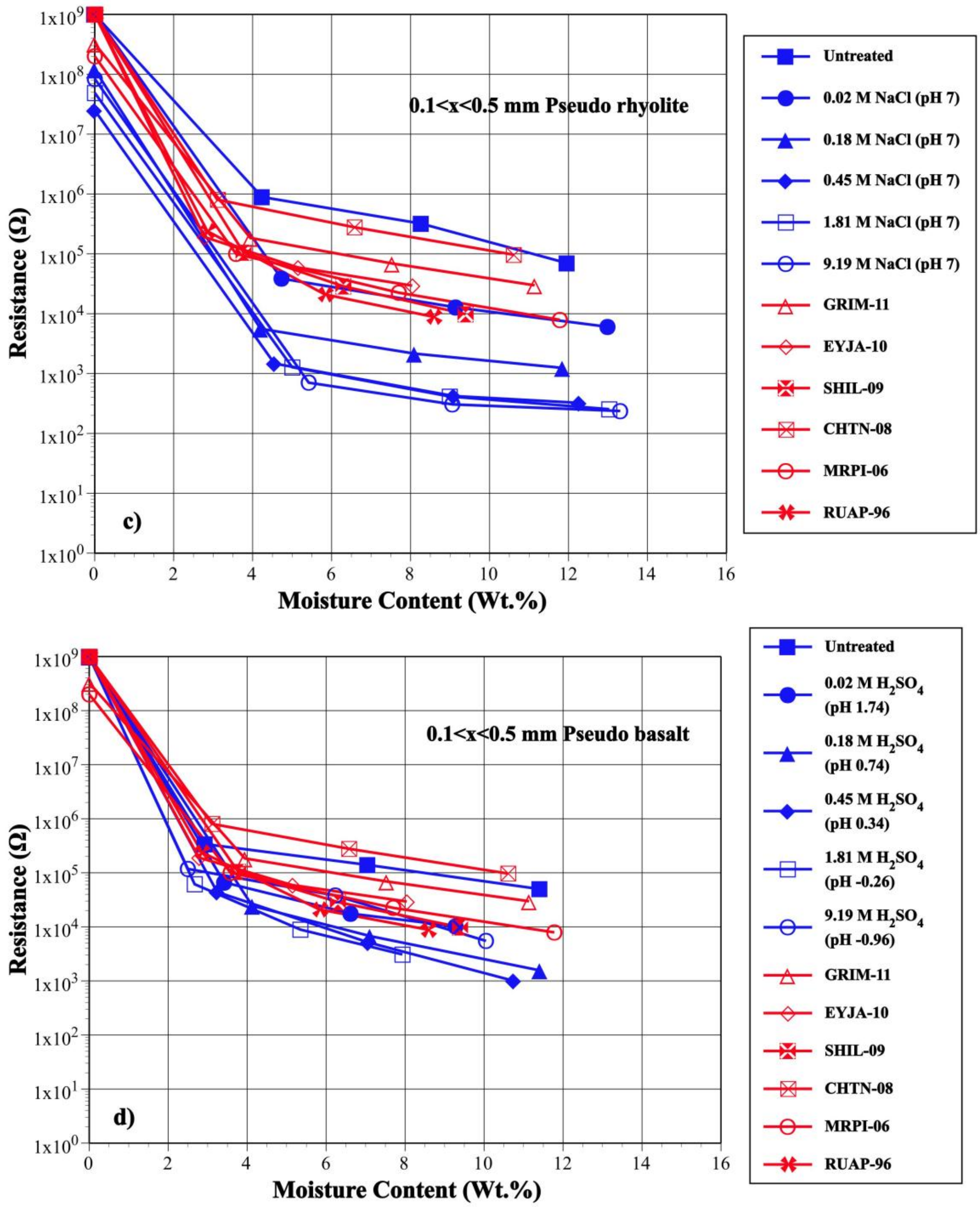


Figure 3.7: Results from the moisture content analysis which show the trend of decreasing electrical resistance with increasing moisture content. **Figures 3.7a** and **b** underline the influence of grain size on resistance while **Figures 3.7c** and **d** highlight the influence of dosing concentration on resistance.

3.5.2 Soluble salt content

Whilst moisture content is imperative to the initiation of electrical current through an ash deposit, attached soluble salts provide added ionic content (increased number of electrons for current flow). During the simple leachate test, the much higher resistivity values obtained for leached RUAP-96 ash compared with the fresh RUAP-96 sample suggests the presence of a large volume of readily soluble salts present on the ash before leaching (Table 3.6).

Resistivity values for the seven fresh ash samples are shown in Figure 3.8 and Table 3.6. Because RDBT-09 displayed the lowest resistivity values in both the uncompacted and compacted testing scenarios, it is likely that this sample had a higher soluble salt content than the other fresh ash samples.

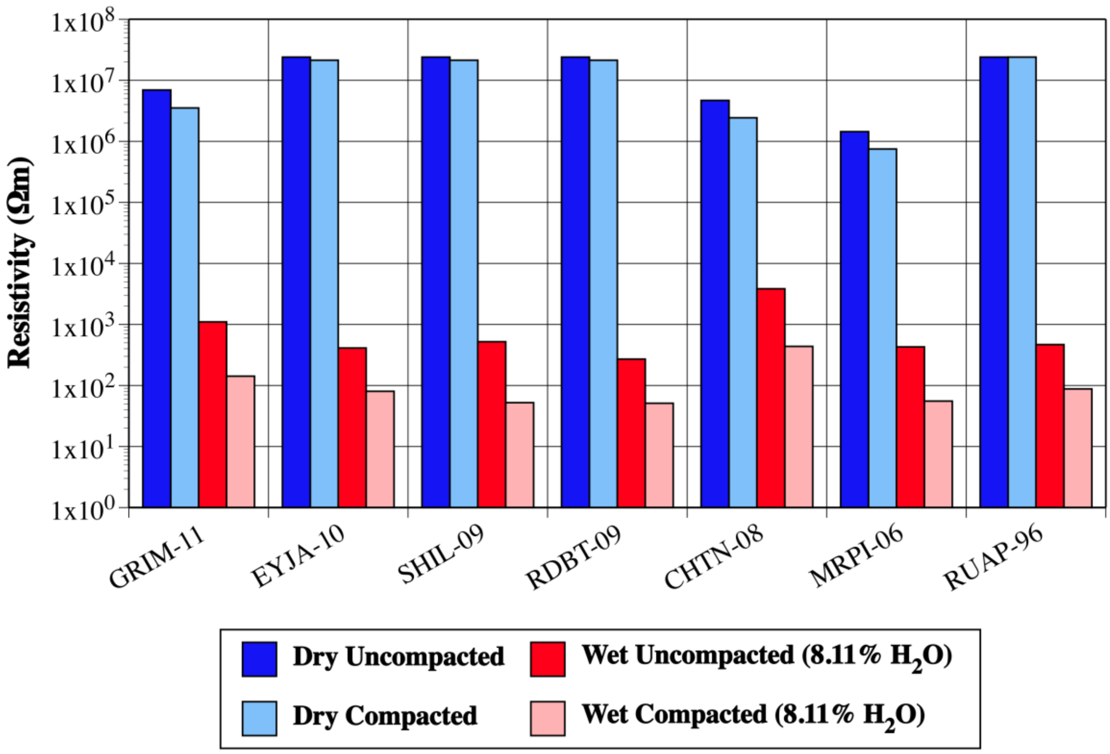


Figure 3.8: Dry and wet (average 8.11 Wt.%) resistivity values for the GRIM-11, EYJA-10, SHIL-09, RDBT-09, CHTN-08, MRPI-06 and RUAP-96 ash samples under uncompacted and compacted scenarios. The resistivity of volcanic ash decreases with increasing compaction, especially once the ash becomes wet.

Table 3.6: Resistivity values for the seven fresh ash samples in the dry, wet, uncompacted and compacted scenarios. The average resistivity values for the seven fresh ash samples (not including the leached RUAP-96 sample (*)) when wet and uncompacted is 1006 Ωm while the average resistivity for wet and compacted fresh ash is 129 Ωm.

	DRY								WET								
	Uncompacted				Compacted				Uncompacted					Compacted			
	Mass (g)	Volume (cm^3)	Bulk Density (g/cm^3)	Resistivity (Ωm)	Volume (cm^3)	ΔVolume (%)	Bulk Density (g/cm^3)	Resistivity (Ωm)	H_2O Added (ml)	Moisture (Wt.%)	Volume (cm^3)	Bulk Density (g/cm^3)	Resistivity (Ωm)	Volume (cm^3)	ΔVolume (%)	Bulk Density (g/cm^3)	Resistivity (Ωm)
GRIM-11	4.97	5.40	0.92	6.9E+06	4.80	11.11	1.04	3.5E+06	0.4	8.88	7.5	0.7	1099	5.4	28.00	1.0	142
EYJA-10	5.16	5.40	0.96	2.4E+07	4.80	11.11	1.08	2.4E+07	0.4	7.97	7.2	0.7	411	5.1	29.17	1.0	80
SHIL-09	4.79	5.40	0.89	2.4E+07	4.80	11.11	1.00	2.1E+07	0.4	9.53	7.2	0.7	521	4.8	33.33	1.0	52
RDBT-09	6.90	5.40	1.28	2.4E+07	4.80	11.11	1.44	2.1E+07	0.4	6.28	7.2	1.0	271	5.7	20.83	1.2	51
CHTN-08	4.86	5.40	0.90	5.0E+06	4.80	11.11	1.01	2.0E+06	0.4	9.02	7.2	0.7	3840	5.1	29.17	1.0	437
MRPI-06	4.99	5.40	0.92	1.4E+06	5.10	5.56	0.98	7.5E+05	0.5	10.33	7.2	0.7	428	5.7	20.83	0.9	55
RUAP-96	6.62	5.40	1.23	2.4E+07	5.40	0.00	1.23	2.4E+07	0.4	7.46	7.2	0.9	468	5.7	20.83	1.2	88
RUAP-96*	6.90	5.40	1.28	2.4E+07	5.40	0.00	1.28	2.4E+07	0.5	7.23	7.2	1.0	5859	5.7	20.83	1.3	1654
AVE.	5.65	5.40	1.05	1.7E+07	4.99	7.64	1.13	1.5E+07	0.4	8.34	7.2	0.8	1612	5.4	25.37	1.1	320

Pseudo ash results indicate a general decrease in resistivity with increasing concentrations used in the dosing procedure (Figure 3.9 and Table 3.7). For example, wet and compacted pseudo basalt dosed in a 0.02 M NaCl solution experienced an average decrease in resistivity by 25% when dosed with 0.18 M NaCl and tested under the same moisture and compaction parameters. With the next added dosage (0.46 M NaCl), the pseudo basalt experienced a further reduction of resistivity by 44%. Pseudo ash that was not treated with any dosing agent consistently showed the highest resistivity values of all the samples (fresh and pseudo), irrespective of the moisture or compaction scenarios.

Tests performed with pseudo ash samples dosed with NaCl generally yielded lower resistivity values than pseudo ashes dosed with equivalent molar concentrations of H_2SO_4. There are several possible explanations for this observation: (1) the low concentrations of H_2SO_4 are not strong enough to cause sufficient mineral precipitation at the ash-liquid interface, (2) ash grains fully saturated by H_2SO_4 cannot allow for precipitation or bonding with the ash surface, or (3) Jacobson (2002) suggests that once condensed onto particles, H_2SO_4 rarely evaporates because of its low saturation vapour pressure. Thus, the minerals precipitated from the H_2SO_4-ash interaction are likely less soluble than those produced by a NaCl compound. However, XRD analysis of the H_2SO_4-dosed rhyolite showed that high (>0.46 M) concentrations seemed to corrode the ash particles to form a clay (mordenite) cement. Pseudo rhyolite dosed with high concentrations (>0.46 M) of H_2SO_4 did not dry despite prolonged oven time. Due to its wet state, pseudo rhyolite ash dosed with H_2SO_4 exhibited lower resistivity values than anticipated during dry tests. The process of surface dissolution at the ash-liquid interface may also control the rates of water adsorption (Delmelle et al., 2005; 2007) and, given the importance of moisture on resistivity, is also a factor that is likely to affect the resistivity of volcanic ash upon deposition.

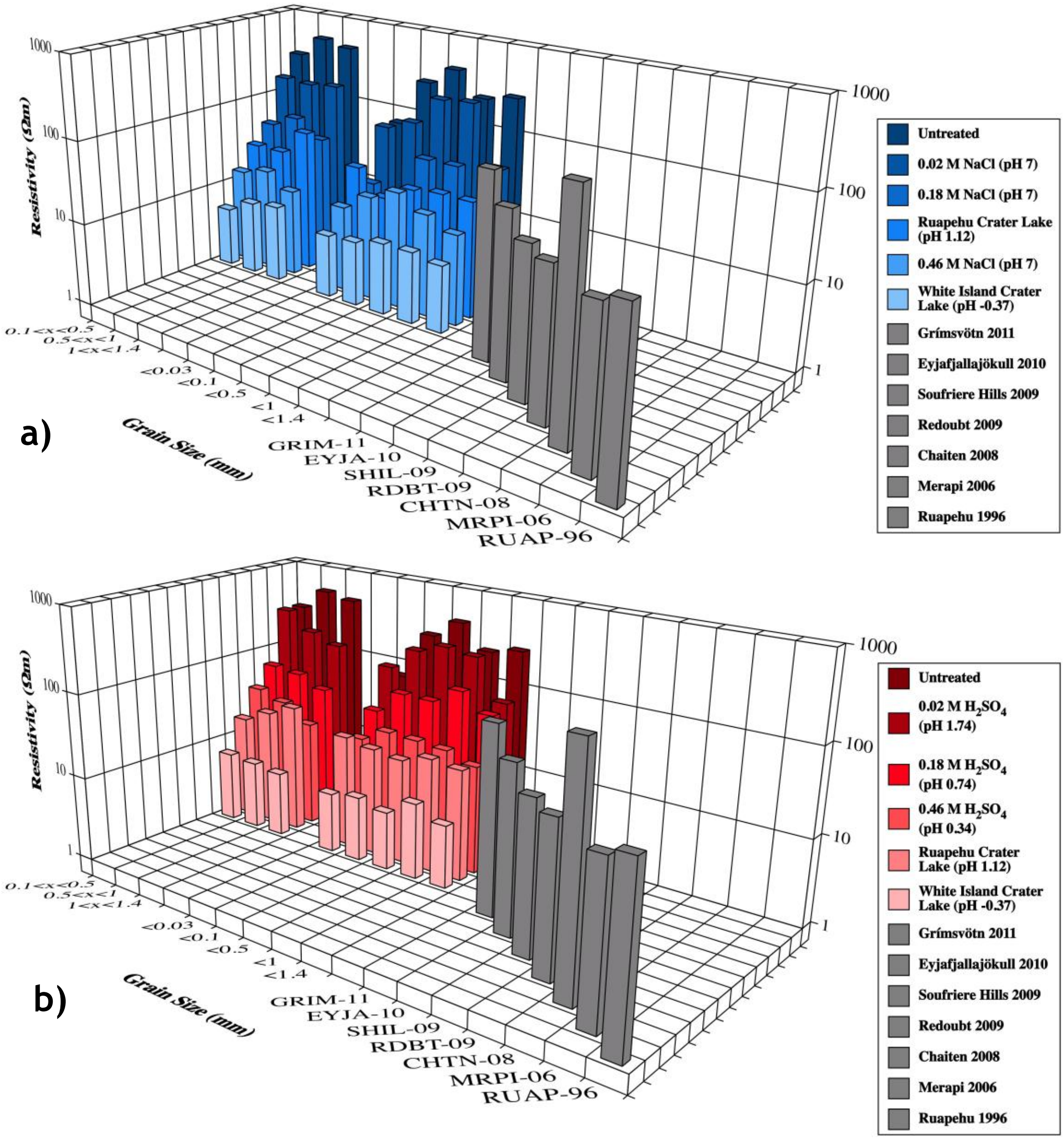


Figure 3.9: Resistivity values for wet and compacted pseudo **a)** rhyolite dosed with varying concentrations of NaCl and **b)** basalt dosed in varying concentrations of H_2SO_4. These graphs show the trend of decreasing electrical resistivity with increasing soluble salt content. Resistivity values for wet and compacted pseudo ashes dosed with crater lake waters from Ruapehu and White Island are also shown for comparison.

Pseudo ash dosed in crater lake water from White Island displayed lower resistivity values than those calculated for ashes dosed in crater lake water from Ruapheu. The higher pH for White Island crater lake water means that a higher number of ions are present within this solution compared with the amount of ions found in crater lake water from Ruapehu. Hence, this increased ionic content results in a less resistive pseudo ash. Resistivity values for pseudo ash dosed in crater lake water from White Island was, on average, 24% lower than those dosed in crater lake water from Ruapehu. When moistened, pseudo ash samples dosed with Ruapehu crater lake water show very low resistivity values despite its pH (1.12) being the equivalent of a 0.075 M H_2SO_4. The unforeseen low resistivity values of pseudo ash samples dosed in Ruapehu crater lake water may be due to the diversity of anions and cations found in the crater lake waters. Thus, to replicate the same electrical resistivity results observed with fresh ash, a higher volume of single compound soluble salts (e.g. NaCl or H_2SO_4) is likely required for dosing compared to that needed for a multiple compound solution.

3.5.3 Grain size and compaction

Previous studies have assumed that fine-grained ash (<0.5 mm) is more conductive than coarse-grained (>1 mm) (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981; Bebbington et al., 2008; Wilson et al., 2009). All grain sizes tested during the dry pseudo ash analysis displayed high resistivity values (e.g. >1.80×10^8 Ωm). When analysed under the wet and compacted scenario, however, the fine-grained pseudo ash (<0.5 mm) most often: (1) had the highest bulk density and (2) was the most conductive (Figures 3.9 and 3.10 and Table 3.8).

Conversely, our results from the resistivity analysis of pseudo ash show that, in the wet and uncompacted scenario, coarse-grained ash (>1 mm) consistently (1) had the highest bulk density and (2) was the least resistive (and therefore most conductive) (Figures 3.9 and 3.10 and Table 3.8). Coarse-grained volcanic ash deposits (>1 mm) have larger voids or pore spaces between grains relative to those in the fine-grained example (<0.5 mm). This allows faster and deeper infiltration of moisture into the ash layer, hastening the rate at which soluble salts are dissolved into a conducting solution over a shorter period of time. This will allow for greater amounts of electrical current to flow through the deposit.

Table 3.7: Average resistivity values for pseudo rhyolite and basalt tested across the range of dosing concentrations. Results show that the electrical resistivity of volcanic ash decreases with increasing soluble salt content, moisture content and compaction.

		DRY								WET								
		Uncompacted				Compacted				Wet Uncompacted					Wet Compacted			
		Mass (g)	Volume (cm^3)	Bulk Density (g/cm3)	Resistivity (Ωm)	Volume (cm^3)	ΔVolume (%)	Bulk Density (g/cm^3)	Resistivity (Ωm)	H2O Added (ml)	Moisture (Wt.%)	Volume (cm^3)	Bulk Density (g/cm^3)	Resistivity (Ωm)	Volume (cm^3)	ΔVolume (%)	Bulk Density (g/cm^3)	Resistivity (Ωm)
UNTREATED	**Rhyolite**	5.38	5.40	1.0	2.16E+07	5.2	3.4	1.0	2.08E+07	0.5	9.45	6.8	0.8	137800	5.5	19.6	1.0	1551
	Basalt	6.63	5.40	1.2	2.40E+07	5.0	6.9	1.3	2.23E+07	0.5	7.69	6.7	1.0	44036	5.1	23.4	1.4	319
0.02 M NaCl	**Rhyolite**	5.23	5.40	0.9	2.40E+07	5.2	3.4	1.0	1.56E+07	0.5	9.81	6.9	0.8	795	5.5	20.0	1.0	191
	Basalt	6.82	5.40	1.2	1.81E+07	4.9	8.3	1.3	2.20E+07	0.5	7.48	6.7	1.0	728	5.2	22.0	1.4	143
0.02 M H_2SO_4	**Rhyolite**	5.09	5.40	0.9	1.66E+07	4.9	9.0	1.0	1.45E+07	0.4	9.24	6.6	0.8	1636	5.4	18.8	1.0	372
	Basalt	6.86	5.40	1.2	2.40E+07	4.9	7.6	1.3	2.21E+07	0.4	7.08	6.7	1.0	836	5.1	22.8	1.4	184
0.18 M NaCl	**Rhyolite**	5.21	5.40	0.9	2.40E+07	5.1	4.8	1.0	2.26E+07	0.4	9.75	7.0	0.8	140	5.5	21.3	1.0	36
	Basalt	6.76	5.40	1.2	1.12E+07	5.1	5.5	1.3	1.02E+07	0.4	7.36	6.6	1.1	206	5.2	20.5	1.3	41
0.18 M H_2SO_4	**Rhyolite**	5.12	5.40	0.9	1.92E+07	5.0	6.9	1.0	1.72E+07	0.5	10.1	6.9	0.8	339	5.5	19.6	1.0	62
	Basalt	6.88	5.40	1.2	2.40E+07	4.9	8.3	1.3	2.20E+07	0.4	7.36	6.6	1.1	261	5.2	19.7	1.4	62
0.46 M NaCl	**Rhyolite**	5.41	5.40	1.0	1.12E+07	5.1	4.8	1.0	8.28E+06	0.5	8.99	6.8	0.8	82	5.6	18.0	1.0	17
	Basalt	6.94	5.40	1.2	1.94E+07	4.9	7.6	1.3	1.63E+07	0.5	6.98	6.6	1.1	75	5.2	20.7	1.4	16
0.46 M H_2SO_4	**Rhyolite**	4.7	5.40	0.8	8.10E+06	5.0	6.9	0.9	2.42E+06	0.4	9.57	6.5	0.7	100	5.1	20.6	1.0	15
	Basalt	6.48	5.40	1.2	2.40E+07	4.9	8.3	1.3	2.05E+07	0.5	7.51	6.5	1.0	111	5.1	21.1	1.3	25

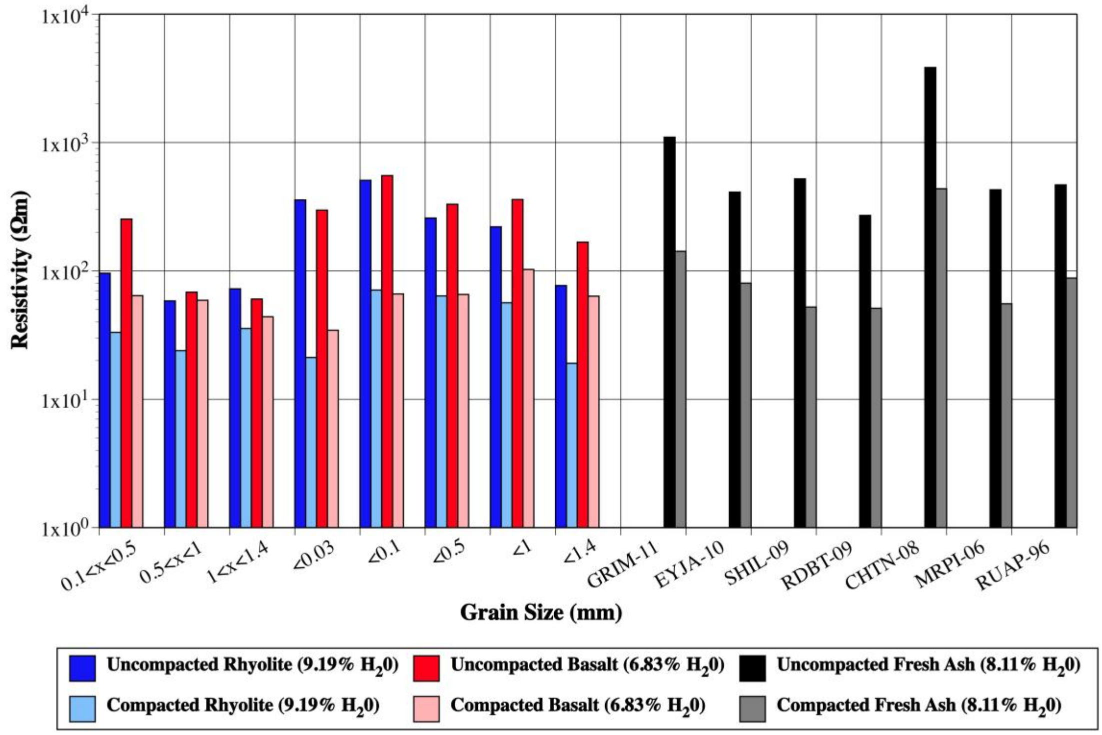


Figure 3.10: Compaction data for wetted **a)** 0.18 M H_2SO_4 pseudo rhyolite and for **b)** 0.18 M H_2SO_4 pseudo basalt. As with the fresh ash samples, pseudo ash displayed a decrease in electrical resistivity with increasing compaction in both the dry and wet scenarios.

Thus, given the trends seen in both the uncompacted and compacted situations, we can conclude that the higher the bulk density of the ash deposit, the more conductive it will be and that all grain sizes ranging from <32 µm to 1.4 mm are capable of exhibiting very low resistivity values (e.g. <100 Ωm) (Figures 3.9 and 3.10 and Table 3.8).

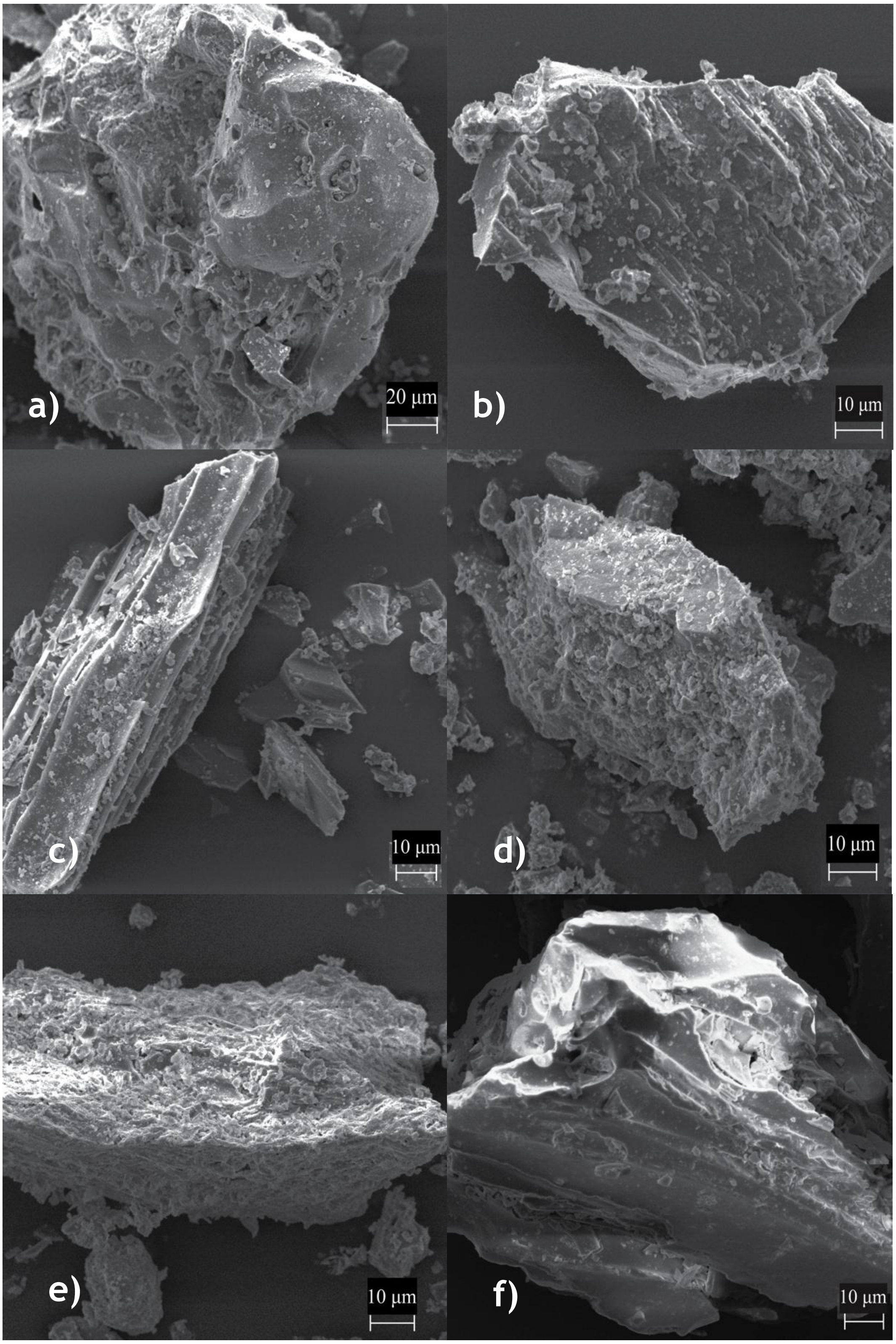
Analysis of the fresh ash supported pseudo-ash findings, where the degree of compaction had a greater influence on resistivity than grain size alone. However soluble salt load still appeared to be the most dominant factor. All fresh ash samples, with the exception of CHTN-08, displayed very similar resistivity values when wet and compacted despite the differences in other variables such as moisture content, bulk density, and grain size distribution (Figures 3.8 and 3.10 and Table 3.6). While CHTN-08 was the most fine-grained fresh ash sample and results most often suggest that fine-grained deposits (<0.5 mm) are the most conductive when wet and compacted, this ash sample was an exception by displaying very high resistivity values under the wet and compacted condition. This suggests that CHTN-08 contained a low amount of soluble salts and that the volume of soluble salts adhered to ash will be dominant in controlling resistivity over both grain size and compaction. Further to this point, while RDBT-09 displayed the highest bulk density and lowest resistivity in uncompacted and compacted scenarios, this ash sample did not contain the largest amount of fine grains in its distribution and its low resistivity suggests that it probably had a higher amount of attached soluble salts.

When moisture was added to very fine-grained pseudo ash (<32 μm) in either the uncompacted or compacted scenarios, the water tended to bead on the ash's surface and the rate of infiltration was very slow (several seconds to minutes). High surface tension on the surface of fine-grained ash inhibits the infiltration of water and is likely the cause of such hydrophobic behaviour (Doerr et al., 1996; 2000). This beading phenomenon was also observed in Mount St Helens' 1980 ash (USGS, 2010) suggesting that fine-grained compacted ash layers are more resistant to water infiltration and may only experience partial adsorption (e.g. only the topmost layers). Additionally, in the context of a contaminated insulator, there may be a race between moisture adsorption needed to decrease the resistivity of ash versus the ability of moisture (e.g. rain) to effectively wash the insulator free of contamination.

A comparison of grain morphologies for the different ash types can be seen in Figure 3.11. Volcanic ash grain morphology will directly influence (1) the rate of water adsorption and (2) the surface area available for the adherence of soluble salts (Delmelle, 2005). It is therefore likely that grain morphology will influence the electrical resistivity of ash. Both pseudo and fresh ash samples used in this study have very similar grain shapes and micro topographies with the exception of CHTN-08, which appears to be highly vesiculated.

Table 3.8: Resistivity data for pseudo rhyolite and basalt dosed with 0.18 M H_2SO_4 showing the influence of grain size on resistivity. Results suggest that all grain sizes are capable of displaying low resistivity values and are therefore equally capable of conducting significant amounts of electrical current given the variety of other controls (e.g. moisture content, soluble salt content, etc.).

0.18 M H_2SO_4		DRY Uncompacted Mass (g)	DRY Uncompacted Volume (cm^3)	DRY Uncompacted Bulk Density (g/cm^3)	DRY Uncompacted Resistivity (Ωm)	DRY Compacted Volume (cm^3)	DRY Compacted Δvolume (%)	DRY Compacted Bulk Density (g/cm^3)	DRY Compacted Resistivity (Ωm)	WET Uncompacted H_2O Added (ml)	WET Uncompacted Moisture (Wt.%)	WET Uncompacted Volume (cm^3)	WET Uncompacted Bulk Density (g/cm^3)	WET Uncompacted Resistivity (Ωm)	WET Compacted Volume (cm^3)	WET Compacted ΔVolume (%)	WET Compacted Bulk Density (g/cm^3)	WET Compacted Resistivity (Ωm)
RYOLITE	0.1<x<0.5	5.66	5.40	1.05	2.4E+07	5.10	5.56	1.11	2.3E+07	0.47	8.30	7.20	0.85	307	5.40	25.00	1.14	47
	0.5<x<1	5.31	5.40	0.98	2.4E+07	5.10	5.56	1.04	2.3E+07	0.43	8.11	6.00	0.96	201	5.70	5.00	1.01	79
	1<x<1.4	4.30	5.40	0.80	4.9E+04	5.40	0.00	0.80	3.5E+04	0.60	14.01	6.60	0.74	50	5.70	13.64	0.86	30
	<0.03	4.02	5.40	0.74	9.4E+06	4.80	11.11	0.84	4.4E+06	0.53	13.19	7.20	0.63	432	5.10	29.17	0.89	60
	<0.1	4.65	5.40	0.86	2.4E+07	4.50	16.67	1.03	2.0E+07	0.49	10.58	7.20	0.71	550	5.40	25.00	0.95	73
	<0.5	5.80	5.40	1.07	2.4E+07	5.10	5.56	1.14	2.3E+07	0.44	7.56	7.20	0.87	485	5.70	20.83	1.09	81
	<1	5.92	5.40	1.10	2.4E+07	5.10	5.56	1.16	2.3E+07	0.48	8.10	7.20	0.89	602	5.70	20.83	1.12	91
	<1.4	5.32	5.40	0.98	2.4E+07	5.10	5.56	1.04	2.3E+07	0.61	11.51	6.90	0.86	89	5.70	17.39	1.04	33
	AVE.	5.12	5.40	0.95	1.9E+07	5.03	6.94	1.02	1.7E+07	0.51	10.17	6.94	0.81	339	5.55	19.61	1.01	62
BASALT	0.1<x<0.5	6.88	5.40	1.27	2.4E+07	4.80	11.11	1.43	2.1E+07	0.47	6.81	7.20	1.02	253	5.10	29.17	1.44	64
	0.5<x<1	7.07	5.40	1.31	2.4E+07	5.10	5.56	1.39	2.3E+07	0.47	6.60	6.00	1.26	68	5.40	10.00	1.40	59
	1<x<1.4	7.30	5.40	1.35	2.4E+07	5.40	0.00	1.35	2.4E+07	0.56	7.66	6.30	1.25	60	5.70	9.52	1.38	44
	<0.03	5.31	5.40	0.98	2.4E+07	4.80	11.11	1.11	2.1E+07	0.57	10.73	6.60	0.89	297	5.10	22.73	1.15	34
	<0.1	5.75	5.40	1.06	2.4E+07	4.80	11.11	1.20	2.1E+07	0.46	7.94	7.20	0.86	553	4.80	33.33	1.29	66
	<0.5	7.80	5.40	1.44	2.4E+07	4.80	11.11	1.62	2.1E+07	0.46	5.94	7.20	1.15	331	5.40	25.00	1.53	66
	<1	8.13	5.40	1.51	2.4E+07	5.10	5.56	1.59	2.3E+07	0.43	5.27	6.90	1.24	360	5.70	17.39	1.50	103
	<1.4	6.78	5.40	1.26	2.4E+07	4.80	11.11	1.41	2.1E+07	0.54	7.91	5.40	1.35	167	4.80	11.11	1.52	64
	AVE.	6.88	5.40	1.27	2.4E+07	4.95	8.33	1.39	2.2E+07	0.49	7.36	6.60	1.13	261	5.25	19.78	1.40	62


a)
20 µm
b)
10 µm
c)
10 µm
d)
10 µm
e)
10 µm
f)
10 µm

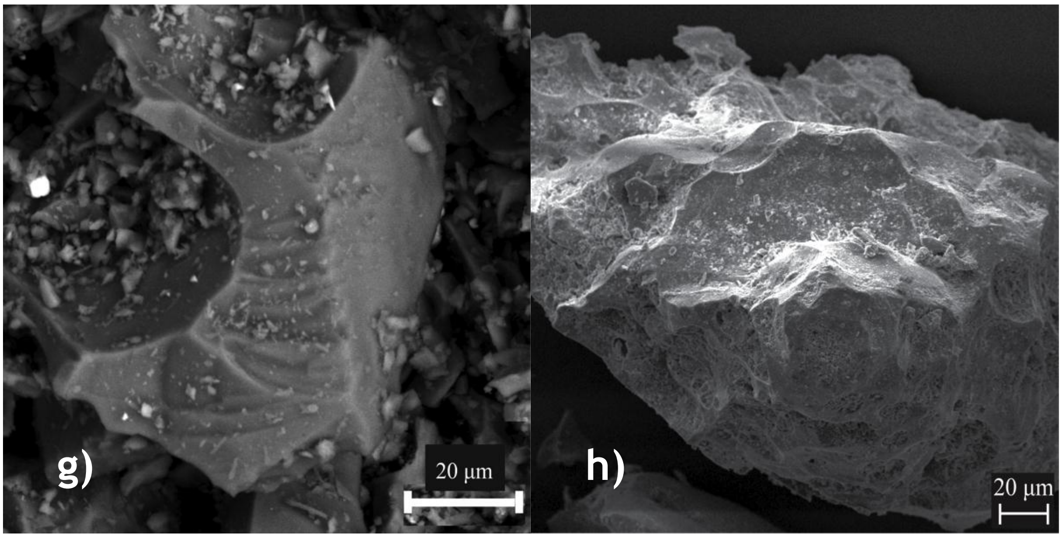


Figure 3.11: SEM images for **a)** 0.18 M H_2SO_4 pseudo rhyolite, **b)** 0.18 M H_2SO_4 pseudo basalt, **c)** 0.18 M NaCl pseudo rhyolite, **d)** 0.18 M NaCl pseudo basalt, **e)** CHTN-08, **f)** MRPI-06, **g)** RDBT-09, **h)** RUAP-96. The porosity/micro topography of volcanic ash directly influences the amount of surface area to which volcanogenic volatiles can adhere. It is therefore likely that ash morphology will have an effect on its electrical resistivity.

3.5.4 Composition

Our pseudo ash data suggests that the differences in ash composition have little effect on electrical resistivity. Average resistivity values for the pseudo rhyolite and basalt are comparable to one another (Figure 3.12), indicating that the dosing agents used on the pseudo ash worked effectively on either composition. Despite the compositional differences between the pseudo and fresh ashes, similar trends suggest that the soluble salt component is dominant over ash composition in controlling resistivity. However, the inability to dry the pseudo rhyolite suggests that ash with high silica content may undergo more vigorous chemical reactions with volatiles in the volcanic plume, particularly the sulphates.

The pseudo ash most analogous to the average resistivity of the fresh ash samples is a crushed rhyolite ash dosed with 0.18 M H_2SO_4 using a 3:1 (cm^3:ml) ash-solution ratio. However, basalt is the preferred pseudo ash composition due to its ability to dry rapidly and thus provide realistic resistivity values in its dry state. NaCl concentrations between 0.02 M and 0.18 M represent a comparable concentration to the adsorbed salts found on fresh ash and, when applied to a basalt proxy, will be a suitable replication of freshly fallen volcanic ash. This pseudo-ash will be reproduced for use in future experiments.

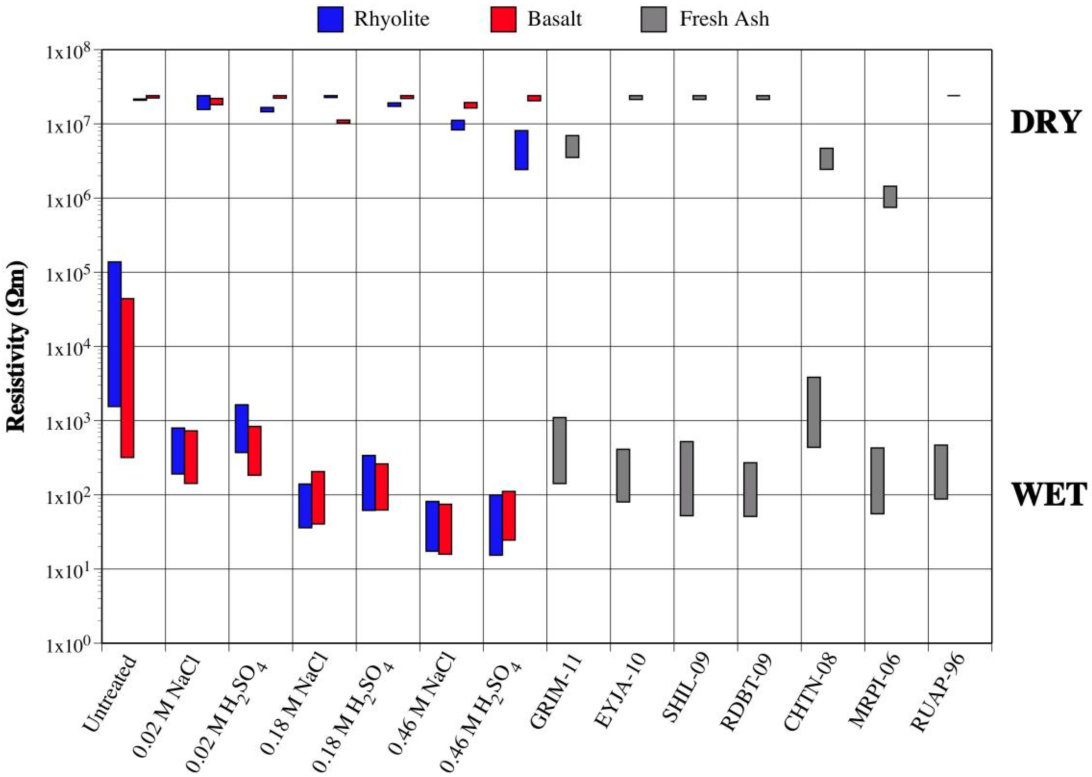


Figure 3.12: Average resistivity values for uncompacted (top values) and compacted (bottom values) for pseudo and fresh ashes under the dry and wet scenarios. Each floating bar represents a range of likely resistivity values for that particular ash given the variation of other controls (e.g. moisture content, grain size, volume, bulk density, etc.). Average resistivity values for pseudo rhyolite and basalt are comparable to each other, however, pseudo basalt appears to be the most conductive across the majority of dosing concentrations.

3.6 CONCLUSIONS

Our characterisation of the electrical properties of volcanic ash is the first attempt to fully examine the variables most influential in controlling the electrical resistivity (conductivity) of volcanic ash. The following conclusions can be drawn from this study:

1) The resistivity of volcanic ash decreases with:
    a. Increasing moisture content (decreasing Ωm with increasing moisture content (Wt.%));
    b. Increasing soluble salt content (decreasing Ωm with increasing molarity (M));

c. Increasing compaction (decreasing Ωm with increasing bulk density (g/cm^3)).

2) Dry volcanic ash is highly resistant to the flow of electrical current. It is therefore unlikely that dry volcanic ash will cause ash-induced flashover on HV insulators;

3) All fresh ash samples, with the exception of CHTN-08, displayed very similar resistivity values when wet and compacted despite the differences in other variables such as moisture content, bulk density, and grain size distribution. High resistivity values for CHTN-08 suggest that this sample was either leached before collection or that there was insufficient gas/aerosol-ash interaction to create significant volumes of soluble surface material. Results from the pseudo ash analysis show that, if wet, the electrical resistivity of volcanic ash will decrease with increasing soluble salt content;

4) The risk of flashover is largely independent of grain size. All grain sizes (<32 µm to 1.4 mm) can exhibit low resistivity values (ρ <100 Ωm) and therefore have similar potential to cause flashover on HV insulators provided there is sufficient moisture content, compaction and soluble salt content. Our results confirm (1) the potential of coarse (>1 mm) ash deposits to display similarly low levels of resistivity as those found in fine-grained (<1 mm) values, in either the uncompacted or compacted scenario and (2) that compaction is a greater influence than grain size on conductivity of volcanic ash. Cleaning of HV insulators should therefore take place immediately after deposition to avoid compaction and consequent increased conductivity of the deposit;

5) In the uncompacted scenario, coarse-grained (>1 mm) ash may be the most conductive due to increased permeability which allows for faster and deeper infiltration of moisture into the ash layer, hastening the rate at which soluble salts are dissolved into a conducting solution. Very fine-grained ash (e.g. <32 µm) may display water-repellent behaviour due to

the high surface tension of the deposit which inhibits infiltration of moisture;

6) Once compacted, fine-grained ash (<0.5 mm) is often the most conductive due to the increased number of pathways for the flow of electrical current (increased contact between grains);

7) Our analysis shows that the simple dosing method used in this study is an appropriate and easily repeatable procedure for the creation of a suitable pseudo ash for future use in contamination testing of HV transmission equipment. Our results indicate that a pseudo basalt dosed with a NaCl solution between 0.02 and 0.18 M will demonstrate equivalent electrical properties as freshly fallen volcanic ash;

8) Our method for testing the resistivity of volcanic ash samples is appropriate for small volume, in-field analysis and this data is useful for electricity and risk managers looking to mitigate the hazards from volcanic ash contamination of HV equipment, in particular the issue of insulator flashover.

3.7 IMPLICATIONS

Currently, there is no standard method used to test the conductivity of volcanic ash during a volcanic eruption. Given the lack of instrumentation available for rapid analysis of the electrical conductivity found in fresh volcanic ash, our method of resistivity analysis is appropriate for small volume, in-field applications. The apparatus used in this study are typical of those employed for electrical measurements within power companies and thus should be easily accessible for rapid measurement at any given time. Resistivity measurements taken at the first opportunity during an ashfall event would be useful for rapid risk assessment models looking to predict the likelihood of ash-induced failure on electric power systems. Avoiding insulator flashover in the first instance will prevent potential cascading failure elsewhere on the power network and thereby fortify the provision of electricity to society.

It would be useful to identify resistivity values that are likely to initiate sufficient current through ash deposits to cause insulator flashover. If resistivity thresholds can be identified, in-field measurements during a volcanic ashfall will aid in the safe management of power transmission and distribution. This should be a major focus of future work.

Other research that will contribute to the understanding of the flashover phenomenon includes correlation between ESDD and conductivity values for volcanic ash. While this has been touched upon in the past (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981), variable grain size has not been incorporated into the ESDD analysis and this study has identified the importance of grain size and amounts of soluble salts attached to ash particles (a function of surface area). Surface area analysis of volcanic ash samples and variations of soluble salts found on volcanic ash, will help our understanding of the gas/liquid-ash interaction within the plume.

3.8 ACKNOWLEDGEMENTS

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Chapter 4: Volcanic Ash Contamination: Limitations of the Standard ESDD Method for Classifying Pollution Severity

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Certification by Co-authors:

If there is more than one co-author then a single co-author can sign on behalf of all.

The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work;
- In cases where the PhD candidate was the lead author of the co-authored work he or she wrote the text.

Name: *Thomas Wilson* Signature: Date: *28 March 2013*

Chapter 4

Volcanic Ash Contamination: Limitations of the Standard ESDD Method for Classifying Pollution Severity

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OVERVIEW

Traditionally, the electrical properties of volcanic ash have been assessed using the equivalent salt deposit density (ESDD) analysis. Rapid and cost-effective risk assessment techniques for volcanic ash contamination on electric power system elements are needed to provide system operator decision support during ashfalls. Chapter 4 identifies a number of limitations in the standard ESDD method for analysing the pollution severity of volcanic ash. Accordingly, this chapter suggests an alternative, simpler and more rapid approach to measuring the electrical characteristics of volcanic ash at the onset of fallout (Chapter 3).

4.1 ABSTRACT

The pollution severity of airborne contamination on high voltage insulators has traditionally been quantified by calculating the contaminant's equivalent salt deposit density (ESDD). Volcanic ash is a rare but severe form of airborne pollution, and the high conductivity of wet volcanic ash (often >1.3 x 10^{-4} S/cm) can cause pollution-induced insulator flashover. This chapter presents the ESDD and non-soluble deposit density (NSDD) for four different fresh volcanic ash samples and two ash proxies measured at different thicknesses using a standardised plate test. Results show that there is a log-linear increase of ESDD with increasing NSDD. Tests indicate that a 3 mm thick deposit (NSDD between 158 and 231 mg/cm^2) of fresh volcanic ash yields an ESDD between 0.02 and 0.7 mg/cm^2, suggesting that ash can have high contamination severity and therefore potential to cause pollution-induced insulator flashover. Whilst the ESDD/NSDD method provides direct analysis of the ionic content of a contaminant, the procedure is time consuming, cannot accommodate the high NSDD of volcanic ash for site pollution severity classification and does not account for changes in the contaminant's electrical conductivity under different environmental, chemical and physical conditions. Given these limitations, this study proposes an alternative, simple yet more comprehensive technique for investigating the electrical properties of volcanic ash by means of direct resistivity analysis.

4.2 INTRODUCTION

It has long been established that electric power systems are vulnerable to pollution-induced insulator flashover and subsequent interruption of service (Adler et al., 1948; Lambeth, 1971; Jolly, 1972; IEEE Working Group, 1979; Gencoglu and Cebeci, 2008; Baker et al., 2009). Volcanic ash is a rare but severe form of airborne pollution. Worldwide accounts have reported adverse impacts to power systems from volcanic ash contamination, with ash-induced insulator flashover being the most common (Chapter 2). The product of explosive volcanic eruptions, volcanic ash consists of two primary components: (1) non-soluble, pulverised fragments (<2 mm particle diameter) of rock, minerals and glass (SiO_2); and (2) soluble salts which form on the surface of ash particles during ash-gas/aerosol interaction within the volcanic plume (Witham et al., 2005). These salts supply ionic content to an otherwise electrically inert material. The fine-grained nature of volcanic ash makes it a good retainer of moisture, and once the attached salts are dissolved into solution (e.g. by dew, fog or light rain), the ash becomes a conductive electrolyte (Chapter 3).

Equivalent salt deposit density (ESDD) is a standard International Electrotechnical Commission (IEC) parameter for Type A pollution (where solid pollution with a non-soluble component is deposited onto the surface of an insulator). An industry practise since the 1950s, the ESDD or 'Solid Layer' method equates the amount of sodium chloride (NaCl) required to yield the same conductivity as the contaminant when dissolved in the same volume of water. Upon calculation, ESDD values are classified into insulator-specific site pollution severity (SPS) indexes provided in IEC 60815-1 (2008). As a guide for this chapter, however, an example of exposed ESDD levels for different pollution severities is shown in Table 4.1.

Table 4.1: ESDD classifications for SPS (after Karady and Farmer, 2007).

ESDD (mg/cm^2)	Pollution Severity
0-0.03	Very Light
0.03-0.06	Light
0.06-0.1	Moderate
>0.1	Heavy

The non-soluble deposit density (NSDD) is another standard pollution parameter prescribed by IEC 60815-1 (2008) that is used to quantify the amount of non-soluble residue on contaminated insulators (also expressed in mg/cm^2). Previous work suggests that the non-soluble component of volcanic ash is a poor conductor (Wright et al., 2009) and the sensitivity of salt deposit density is higher on flashover voltage than that of NSDD (Ramos et al., 1993). However, other studies have shown that inert, non-soluble pollution can greatly reduce the flashover voltage of HV insulators (Ishii et al., 1996; Sundararajan and Gorur, 1996). Insoluble deposits do not contribute directly to conductivity but instead convert the smooth surface of an insulator into a rough, irregular one which, in turn, can affect (1) the run-off rate of soluble material, (2) the hydrophobicity of the insulator surface, (3) the evaporation rate of the wetted layer, and (4) the local electric field strength (Farzaneh and Chisholm, 2009).

Whilst most forms of pollution such as salt, combustion emissions, dust (e.g. earth, fertiliser, metallic, coal and feedlot), smog, and defecation (e.g. bird streamers) have been identified and studied in some detail (CIGRE TF 33.04.01, 2000; CIGRE WG C4.303, 2008), very little information exists on the ESDD of volcanic ash (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995; Gutman et al., 2011). This chapter complements the existing knowledge of insulator contamination in different polluted environments by presenting the results from ESDD tests for four fresh volcanic ash and two comparative pseudo (artificial) ash samples. Based on the findings, an assessment of the overall suitability of the ESDD method for quantifying the pollution severity of volcanic ash is considered. It is intended this will aid power system operators to better understand the potentially wide-ranging physical, chemical and electrical characteristics of volcanic ash.

4.3 SAMPLES

4.3.1 Fresh ash samples

The low frequency of explosive eruptions and logistical difficulties in collecting pristine volcanic ash meant only four ash samples collected from four different eruptions were available for analysis. The volcano and eruption dates for each ash are listed in Table 4.2. All samples had been stored in dry conditions within sealed polyethylene bags since collection. Non-essential movement was minimised to reduce modification of ash properties.

Freshly fallen volcanic ash loses its soluble content rapidly in the presence of moisture (such as rain or wet soil) so it is imperative that ash collection be carried out shortly after an eruption and the ash adequately stored to avoid leaching or erosion of the soluble components.

Table 4.2: Fresh ash samples used in this study. Samples were collected by the authors or provided by research affiliates.

Sample ID	Volcano	Country	Date of collection
SDKE-10	Shinmoe-dake	Japan	2-Feb-11
SHIL-09	Soufriere Hills	Montserrat (UK)	27-Nov-09
CHTN-08	Chaiten	Chile	28-May-08
RUAP-09	Ruapehu	New Zealand	18-Jun-96

4.3.2 Pseudo ash samples

To augment our limited fresh ash samples, a pseudo ash was developed to replicate the physical and electrical properties of freshly fallen volcanic ash to test against the fresh volcanic ash samples.

Unweathered Stoddart olivine basalt (from Halswell Quarry, Lyttelton volcano, New Zealand) (Guard, 1999) was chosen as the non-soluble volcanic component for our ash proxy. It has been argued that fine-grained ash deposits (e.g. <0.5 mm particle diameter) have a higher surface area per-unit-volume and will therefore contain more soluble material than that of coarse-grained deposits (e.g. >1 mm particle diameter) (An et al., 2002; Chapter 3). Thus, to investigate whether particle size has any effect on ESDD, two different pseudo ashes were created: (1) a predominantly fine-grained fraction (<0.1 mm) and (2) an ash with a coarse-grained component (<1 mm). These were manufactured by dry sieving the original crushed and pulverised product.

Accurate replication of soluble salts found in fresh volcanic ash is best achieved using a brine (NaCl) dosing solution with a molar concentration between 0.02 and 0.18 M at a ratio of 3:1 (ash:brine solution). Thus, a 0.15 M salt solution was added to the non-soluble pseudo material to serve as an appropriate dosing agent for ESDD tests.

4.4 PROCEDURES

4.4.1 Particle size distributions

To analyse the influence of particle size on the ESDD of volcanic ash, distributions for all ash samples (fresh and pseudo) were determined using a HORIBA Partica LA-950 laser diffraction particle size analyser. Each fresh or pseudo ash was sampled twice and measured a minimum of five times in the particle size analyser to ensure reliability of the results. The output values were averaged and the distribution curves are shown in Figure 4.1.

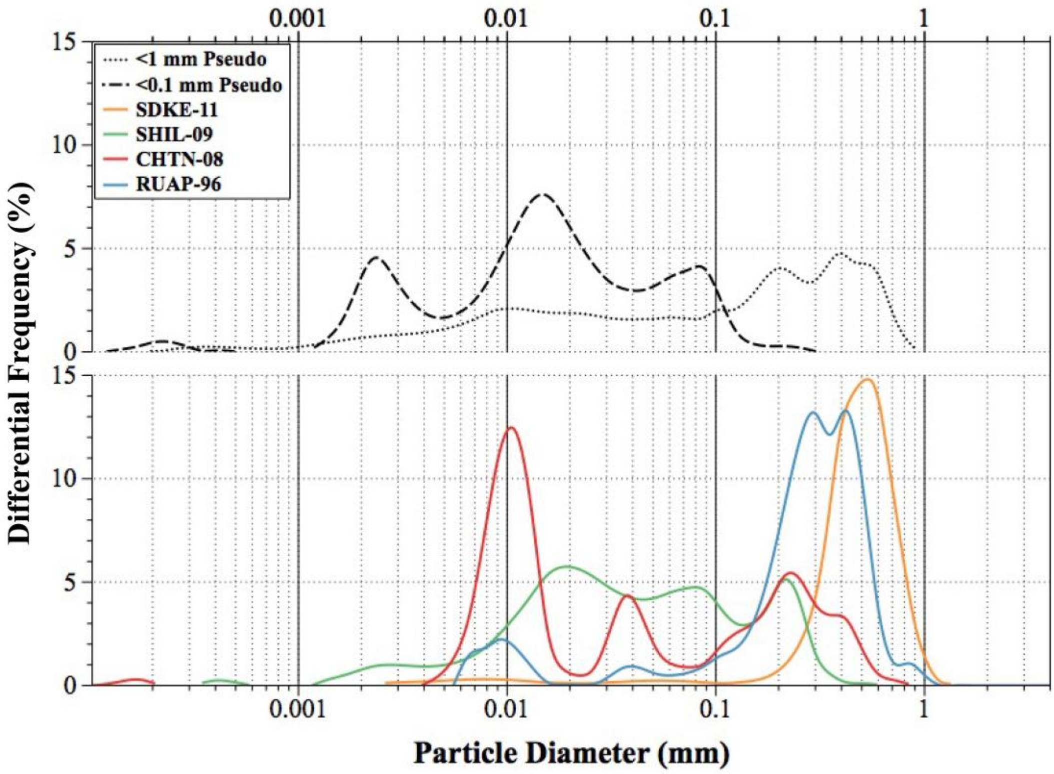

Figure 4.1: Grain size distributions for the four fresh and two pseudo ash samples used in the ESDD analysis.

4.4.2 Application of the pollution layer

Considering (1) the importance of retaining soluble surface salts inherent in freshly fallen volcanic ash, (2) the potential for volcanic ash to be deposited in large quantities (e.g. >10 mm thicknesses) and (3) the lack of appropriate testing standards pertinent to volcanic ash, the pollution layer for ESDD tests was applied using dry volcanic ash rather than the flow-on or dipping techniques proposed in IEC 60507 (1991) and IEEE Std 4 (1995).

Although this made the procedure more difficult and time consuming, it replicated a realistic deposit of volcanic ash that was guaranteed to retain its soluble salt content. Previous Solid Layer tests on volcanic ash (Nellis and Hendrix, 1980; Matsuoka et al., 1995; Gutman et al., 2011) have not used the plate contamination method applied for ESDD measurements in Section 4.4.3.

4.4.3 ESDD measurements

The ESDD method used in this study was adapted from the standardised procedure outlined in IEC 60815-1 (2008). A simple plate test was devised to explore the relationships between ash thickness (the parameter most useful to volcanic scientists), NSDD, volume conductivity and ESDD. The plate test assumes uniform thickness and complete coverage of the insulator (e.g. top and bottom surfaces). A range of accumulations from light dusting (0.5 mm) to heavy deposits (10 mm) was investigated. A 10 x 10 cm Perspex plate (0.3 cm thick) was used for the plate tests. The plate was artificially contaminated to measured thicknesses of 0.5, 1, 3, 6 or 10 mm. However, the limited amount of fresh ash available meant that (1) only a small surface area (10 x 10 cm) was contaminated, and (2) fresh ash samples could only be used for plate tests up to 6 mm thick, whereas the pseudo ash, which could be easily reproduced, was tested up to thicknesses of 10 mm.

The entire deposit was carefully collected by brushing the ash into a cylindrical, plastic container (diameter: 26 cm, height: 17 cm). 700 ml of deionised water (<3 μS/cm) was then added and mixed with the ash to ensure complete saturation. Both Nellis and Hendrix (1980) and Gutman et al. (2011) suggest that some volcanogenic solubles can take hours to dissolve into solution. Thus, while typical ESDD tests for other forms of pollution require only 2 mins of saturation time before measurement, the contained ash slurry was agitated by hand every 10 mins for a total of 30 mins to aid the dissolution of attached soluble salts.

After the dissolution period, the volume conductivity σ_θ of the water (S/cm) at the temperature θ (°C) was measured using a Eutech Cyberscan

PC300 conductivity meter. As per IEC 60507 (1991), IEEE Std 4 (1995), and IEC 60815-1 (2008), the value σ_θ was then corrected to a reference temperature of 20 °C.

To ensure reliability of results, three tests were performed at each fresh ash thickness. Ample amounts of pseudo ash allowed for six tests per thickness. The container was thoroughly rinsed with deionised water and then dried with a clean cotton rag before each repetition.

4.4.4 NSDD measurements

Non-soluble matter was separated from the ash/water mixture using pre-dried and weighed filter paper and a funnel. The residuum was dried in an oven at 100 °C for 12 hours before NSDD for fresh and pseudo ash samples was calculated using the procedure outlined in IEC 60815-1 (2008).

4.5 RESULTS AND ANALYSIS

4.5.1 ESDD/NSDD relationships

Results for average calculations of NSDD, volume conductivity, salt content, and ESDD values for the four fresh ash and two pseudo ash samples are presented in Figure 4.2 and Table 4.3. Results show that the ESDD of volcanic ash increases log-linearly with increasing ash thickness and/or NSDD. This means that increasing accumulations of ash (a function of time) on HV insulators will lead to an increase in ESDD and therefore a decrease in flashover voltage.

Despite CHTN-08 often having a higher NSDD, it consistently had the lowest ESDD and therefore salt content (average 0.2 Wt.%) of all fresh ash samples. These unusually low values suggest that CHTN-08 was either leached before collection or that there was insufficient ash-gas/aerosol interaction within the volcanic plume to create significant volumes of soluble surface salts.

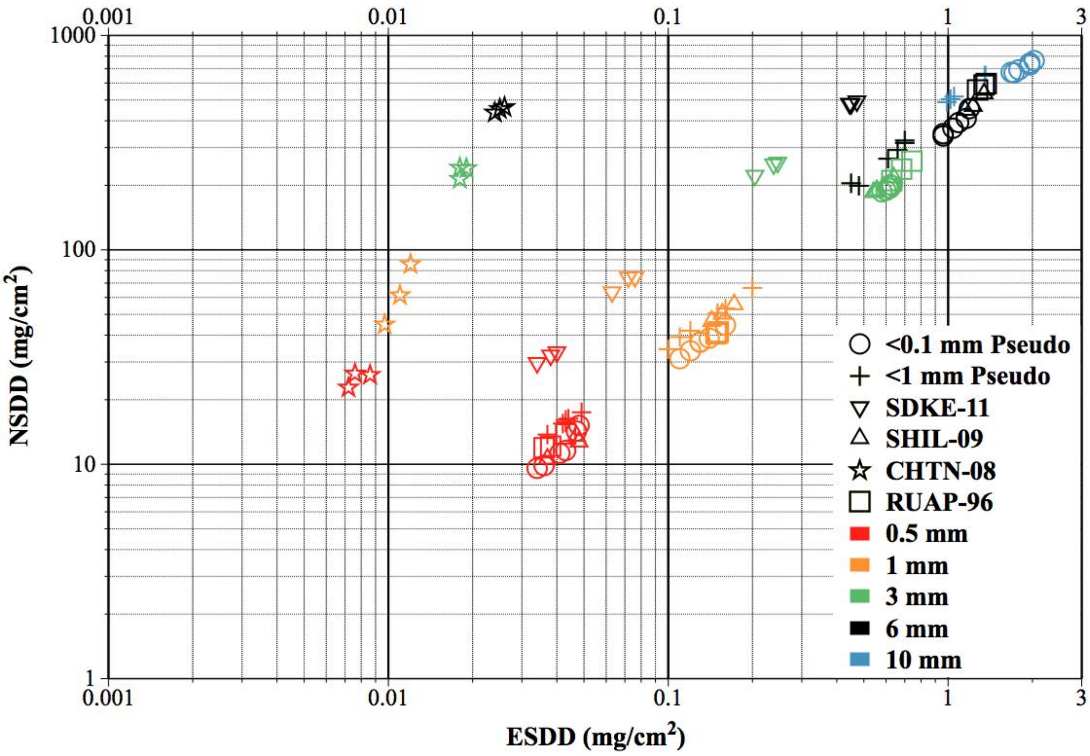

Figure 4.2: ESDD vs. NSDD for fresh and pseudo ashes at varying thicknesses.

Analysis of the pseudo ash results provides further insight into the relationship between NSDD and ESDD of volcanic ash. Comparing the two pseudo ashes shows that the fine-grained ash (<0.1 mm) consistently had a higher salt content (average 3.1 Wt.%) than the coarse-grained comparator (average 2.4 Wt.%). However, with each thickness examined, the coarse-grained pseudo ash (<1 mm) most often had a higher total mass, NSDD, volume conductivity, and ESDD. Thus, while the pseudo ashes were created from rock of the same chemical composition and prepared using identical dosing procedures, the fine-grained pseudo ash had a higher soluble salt content despite it having lower NSDD values than that of the coarse-grained comparator. This suggests that particle size has an influence on the ESDD (and conductivity) of a volcanic ash deposit. However, this and others controls (geomorphology, porosity, and chemical composition) are still likely to be dominated by the soluble salt parameter (Chapter 3).

Table 4.3: Averages for the fresh and pseudo ash parameters obtained during the ESDD analysis. SPS abbreviations: VL=Very Light, L=Light, M=Moderate, H=Heavy.

	Thickness (mm)	Total Mass (g)	NSDD (mg/cm^2)	Vol. σ (μS/cm)	Salt Cont. (Wt.%)	ESDD (mg/cm^2)	SPS
SDKE 11	0.5	3.18	28.9	10.9	1.2	0.04	L
	1	7.09	68.8	20.0	1.0	0.1	M
	3	24.3	158	63.5	0.9	0.2	H
	6	48.5	463	124	0.9	0.5	H
SHIL 09	0.5	1.23	11.8	12.8	3.6	0.04	L
	1	5.10	32.3	43.9	3.1	0.2	H
	3	19.8	181	156	2.9	0.6	H
	6	48.6	468	327	2.6	1.2	H
CHTN 08	0.5	2.51	15.9	2.39	0.3	0.01	VL
	1	6.39	59.6	3.29	0.2	0.01	VL
	3	23.2	217	5.48	0.1	0.02	VL
	6	45.1	425	7.38	0.1	0.03	VL
RUAP 96	0.5	1.27	12.0	11.4	3.1	0.04	L
	1	4.12	39.2	41.9	3.6	0.1	H
	3	23.7	231	184	2.9	0.7	H
	6	58.2	558	350	2.3	1.3	H
<0.1 mm Pseudo	0.5	1.20	11.6	12.0	3.5	0.04	L
	1	3.72	35.3	35.8	3.5	0.1	H
	3	19.5	185	164	3.1	0.6	H
	6	38.7	359	282	2.8	1.1	H
	10	71.3	681	484	2.6	1.9	H
<1 mm Pseudo	0.5	1.58	15.0	12.5	2.7	0.04	L
	1	4.78	44.4	38.6	2.9	0.1	H
	3	26.7	247	162	2.2	0.6	H
	6	57.8	447	313	2.1	1.2	H
	10	95.5	911	518	2.1	2.0	H

4.5.2 Pollution severity

Our analysis shows that, for the three ashes which appear to have not been leached prior to testing (SDKE-11, SHIL-09 and RUAP-96), only a uniform light dusting of 0.5 to 1 mm is required to create heavy pollution severity (according to the general classification of SPS in Table 4.1). This is significant considering the potential for ash deposits to exceed tens of millimetres in thickness during a single ashfall (Chapter 2). An et al. (2002) propose that insulator flashover is imminent once ESDD levels reach 0.4 mg/cm^2, suggesting that a 3 mm deposit of either RUAP-96 or SHIL-09 is sufficient in soluble salt content to cause ash-induced flashover, provided the ash is wet enough to initiate a leakage current across the surface of the insulator.

Of the fresh ash samples, RUAP-96 and SHIL-09 had the highest pollution severities (moderate to heavy), ESDD (0.04 to 1.3 mg/cm^2), and salt content (average 3.0 Wt.%) across the investigated range of thicknesses. Bebbington et al. (2008) found that samples from Mount Ruapehu (RUAP-96) contained total salt concentrations typically between 0.4 and 2.1 Wt.%, which is between four and twenty times more than was observed in ash from the 1980 Mount St Helens (USA) eruption. This agrees with our results which showed that 3-6 mm of RUAP-96 had an ESDD between 0.7 to 1.3 mg/cm^2. This value is more than double that of the ESDD found by Nellis and Hendrix (1980) following the Mount St Helens eruption, where 3-6 mm of 1980 Mount St Helens ash yielded an ESDD between 0.3-0.6 mg/cm^2. These high pollution severity values highlight the danger of ash contamination on HV insulators.

If ESDD calculations for freshly fallen volcanic ash are to be used and interpreted by system operators, it is essential that measurements be taken during or immediately after deposition to ensure pristineness of the test samples. Previous efforts to quantify the ESDD for volcanic ash (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995; Gutman et al., 2011) have used ash that was collected from the environment some time (days to weeks) after the initial fallout. It is therefore unclear whether the ash samples used in those tests had lost some of their soluble salt content (e.g. due to rain leaching) prior to analysis. While the potential for flashover is highest during and immediately after deposition, many volcanic ash samples, even after long periods of repeated wetting, contain slowly soluble components such as sulphate and fluoride compounds that may be extracted over prolonged periods of time (Cronin and Sharp, 2002). Thus, ash deposits may pose a flashover hazard for days to weeks following an eruption. Cleaning of HV equipment should therefore be carried out at the first opportunity to avoid the latent risk of ash-induced flashover.

4.5.3 Limitations of the ESDD method

For very high values of NSDD relative to ESDD, there is limited data available for IEC 60815-1 (2008) classification of SPS (e.g. the shaded area to the top left-hand side of Figure 4.3).

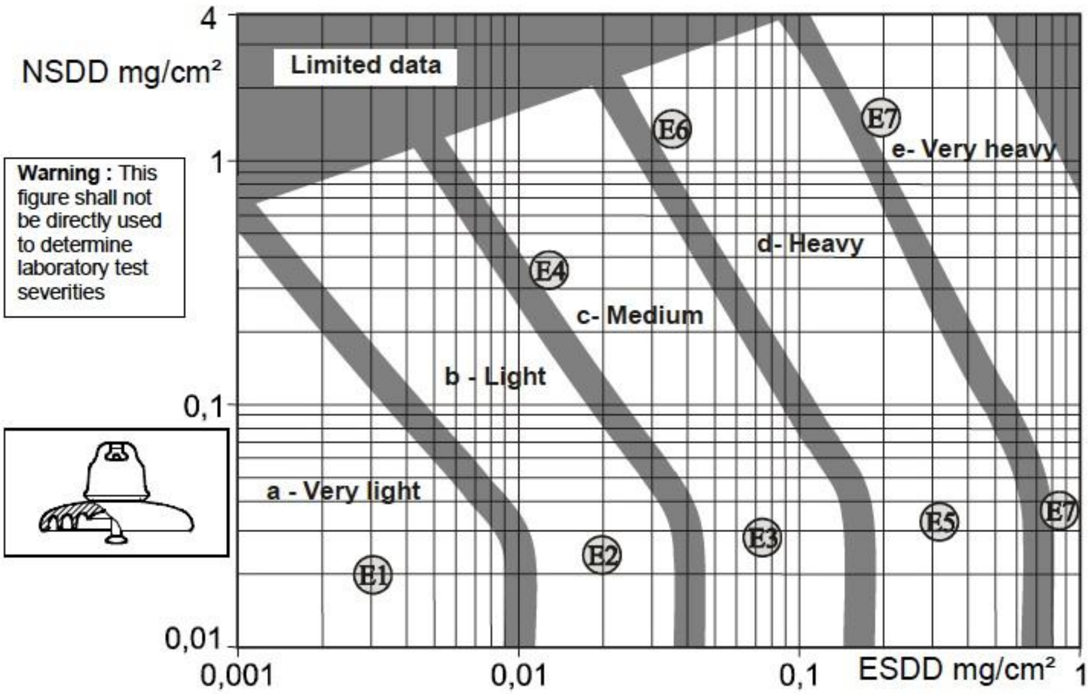

Figure 4.3: Relationship between ESDD/NSDD and SPS for the reference cap and pin insulator (from IEC 60815-1 (2008)).

The extremely high NSDD observed in the ashes used in this study makes it difficult to classify SPS using the guidelines set out in IEC 60815-1. Consequentially, this suggests that the standard ESDD/NSDD analysis is currently unsuitable for volcanic ash contamination containing NSDD >4 mg/cm^2.

If a volcanic ash deposit is sufficiently conductive, it will initiate a leakage current on an HV insulator. The presence of leakage current will be dependent on the conductivity of the ash, which is influenced by many factors. For example, compacted volcanic ash deposits have a significantly lower resistivity than uncompacted layers (Figure 4.4) (Chapter 3). Laboratory Solid Layer tests, such as the ones carried out in this study, are representative of uncompacted deposits of volcanic ash. Results from both Chapter 3 and this study show that the RUAP-96 sample is slightly less resistive (more conductive) than SHIL-09 in the uncompacted scenario. However, once compacted, SHIL-09, a more fine-grained ash, is less resistive to current flow. Moisture content, compaction and particle size are important parameters in promoting the conductivity of volcanic ash but are not accounted for in the ESDD analysis. Thus, a different means of analysis is required to account for the other variables influencing the conductivity of an ash deposit.

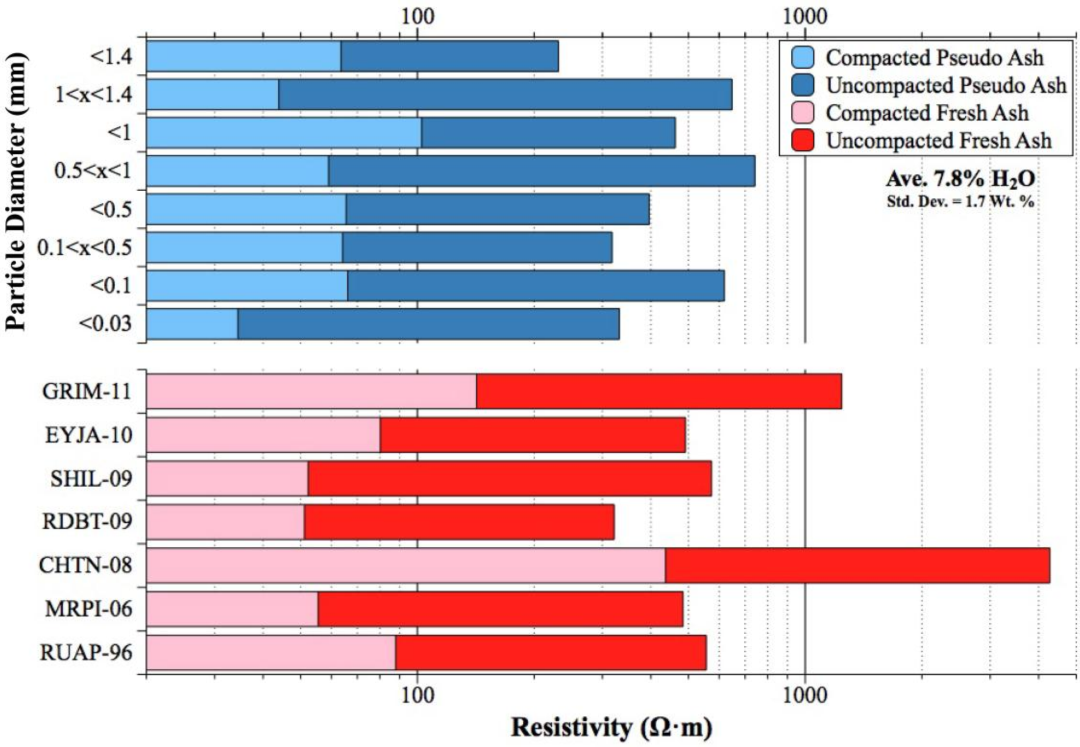

Figure 4.4: Resistivity values for wet (average 7.8 Wt.% moisture content) compacted (lighter shades) and uncompacted (darker shades) fresh (in red) and pseudo (0.18 M NaCl Basalt, in blue) ashes (adapted from Chapter 3).

Large volumes of volcanic ash may be deposited in a very short space of time (e.g. several mm/hour), making volcanic ash very different from other types of airborne pollution. In the case of Nellis and Hendrix (1980), insulators that flashed over from suspected ash contamination during the 1980 Mount St Helens eruption had to be removed from service, transported to a laboratory (being careful not to lose some of the ash deposit while in transit), and the deposits carefully collected from the insulator surface before ESDD analyses could be performed. In addition, the NSDD component of the test demands filtration of the water/ash mixture and several hours of drying time before NSDD calculations can be made. Thus, if the procedure cannot be performed on-site, the ESDD/NSDD method requires much time. This emphasises the need for a more rapid means of analysis, as decisions to initiate mitigation strategies rely heavily on the pollution severity of the ash.

Emergency power system management requires a rapid means of pollution analysis to support sound decision making during volcanic ashfalls. Simple evaluations of volcanic ash that highlight gross variations in pollution severity with time and space are perhaps more appropriate for rapid analysis. As a practical tool for measuring site conditions (SPS) during volcanic ashfalls, the ESDD method is insufficient due to the aforementioned limitations.

4.5.4 Alternative analysis

Given the variability of ESDD and NSDD in volcanic ash with every eruption, it is clear that a rapid, in-field testing procedure is needed to quantify the electrical characteristics of volcanic ash at the first instance of ash fallout. The resistivity analysis developed in Chapter 3 can be performed immediately, requires very little time and equipment, better accounts for the physical variables which promote conductivity (e.g. moisture content, compaction, grain size and whole rock chemistry), and provides a similar indication of the pollution severity (primarily a function of the soluble salt content) as the ESDD method for freshly fallen volcanic ash. The procedure for the resistivity method is summarised as follows:

- Collect a bulk sample (e.g. >50 g) of clean, unaltered ash from a horizontal surface or directly from the fallout (e.g. in a container or tarpaulin);
- Place a known volume of ash into a pre-fabricated and pre-weighed testing vial or container with fixed plate electrodes. To prevent distortion of the electric field, avoid filling the testing vial above the electrodes;

- Record the mass of the sample so that moisture content can be calculated via loss-on-ignition analysis;
- Apply a voltage across the sample using an ohmmeter and record the resistance. For dry (highly resistant) samples, a high voltage source (e.g. >1 kV) may be required to obtain a reading;
- Using volumetric parameters, calculate resistivity;
- Perform a compaction test by applying a 4.5 kg (10 lb) weight atop the ash sample. Determine the resistance and calculate resistivity for the compacted sample;
- Save bulk and tested samples for additional investigations such as chemical (IC PMS, XRF, XRD, etc.) and particle size analysis.

4.6 CONCLUSIONS AND IMPLICATIONS

A rare but severe form of Type A pollution, volcanic ash can cause pollution-induced insulator flashover and subsequent disruption to power supply. Volcanic ash varies widely in both ESDD and NSDD and therefore pollution severity with each new eruption. Results from this study complement the existing knowledge on insulator contamination and show that very small accumulations of volcanic ash (e.g. 0.5–1 mm thickness) can have high pollution severity and thus potential to cause insulator flashover. This is significant considering the possibility of many tens of millimetres of ash accumulation during a single volcanic eruption.

Several limitations are inherent in the ESDD method when analysing volcanic ash, primarily: (1) the ESDD method does not account for the variations in electrical conductivity of the ash under different environmental, chemical and physical conditions (e.g. moisture content, compaction, grain size and whole rock chemistry); (2) the time consuming ESDD method cannot rapidly provide pollution severity information to system operators looking to mitigate ash-induced flashover; and, (3) cannot provide IEC 60815-1 (2008) SPS classifications for volcanic ash deposits with NSDD >4 mg/cm^2.

It is essential that volcanic ash be collected and analysed at the first opportunity to provide system operators with useful information that can support the decision to implement mitigation strategies. An emphasis should be made on research leading to 'low-tech' measuring techniques, which, though possibly less precise and sensitive, can be applied locally, easily, and inexpensively. The resistivity method developed in Chapter 3 to characterise the electrical properties of volcanic ash is a fast, simple and comprehensive approach to understanding the potential for ash-induced flashover on HV insulators.

4.7 ACKNOWLEDGEMENTS

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Chapter 5

Influence of volcanic ash contamination on the flashover voltage of outdoor HVAC suspension insulators

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OVERVIEW

Volcanic ash-induced insulator flashover is the most likely impact to disrupt HV power systems during and/or following an ashfall (Chapter 2). Until now, our understanding has been based on the Mount St Helens study and anecdotal field observations (Chapter 2). A lack of empirical data on the external factors influencing the flashover mechanism has prompted the need for a systematic analysis of the subject. Chapter 5 presents the results from electrical tests carried out to assess the vulnerability of a range of different HV insulators commonly used in New Zealand's transmission system to volcanic ash-induced insulator flashover.

5.1 ABSTRACT

High voltage (HV) station and line insulators used on alternating current (AC) systems are vulnerable to volcanic ash-induced flashover, yet little quantitative data exists on the environmental, volcanological and electrical parameters most influential in reducing their flashover voltage. This chapter presents results from clean-fog rapid flashover tests for 5 different suspension insulators of either ceramic or non-ceramic construction under different environmental and volcanic ash contamination scenarios. Results suggest composite polymer insulators have higher dielectric strength (pollution performance) than ceramic equivalents under light to heavy pollution severities due to their hydrophobic properties. However, all insulators tested here perform comparably when critically contaminated (i.e. both top and bottom surfaces coated in ash). Based on these and other findings, recommendations for best insulator selection and maintenance are provided.

5.2 INTRODUCTION

The process of insulator contamination, associated flashover and subsequent loss of service has been a major problem on electric power systems since their inception in the early 1900s (Baker et al., 2009). Volcanic ash is an infrequent, but potentially highly disruptive form of contamination capable of causing insulator flashover across station and line insulators (porcelain, glass or polymeric) (Chapter 2). Of all eruptive hazards, ashfall can affect the most people because of the wide areas that can be covered by fallout (Blong, 1996). Considering 9% of the world's population lives within 100 km of a historically active volcano (Horwell and Baxter 2006), and the increasing reliance of society on electricity to maintain normal operations, there is a desire to increase power system resilience to volcanic ashfall hazards.

Most efficiently produced by explosive volcanic eruptions, volcanic ash consists of two chief components: (1) non-soluble, pulverised fragments (<2 mm particle diameter) of rock, minerals and glass (SiO_2); and (2) soluble salts which form on the surface of ash particles during ash-gas/aerosol interaction within the volcanic plume (Delmelle et al., 2007). These attached surface salts supply ionic content to an otherwise electrically inert material. Once the attached salts are dissolved into solution (e.g. by dew, fog or light rain) the ash becomes a conductive electrolyte and poses a flashover hazard to the power system (Chapter 3).

While the pollution flashover phenomenon has been studied in great detail (e.g. Adler et al., 1948; Lambeth, 1971; Jolly, 1972; CIGRE Taskforce 33.04.01, 2000; Gencoglu and Cebeci, 2008), little knowledge exists on the pollution performance of HV insulators subjected to volcanic ash contamination. Although anecdotal evidence (e.g. Wilson et al., 2009; Chapter 2) and limited experiments (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995) provide some understanding of ash-induced flashover processes, a systematic examination of this problem has not been conducted to-date. This study presents the results from clean-fog rapid flashover tests for 5 different suspension insulators subjected to a range of contamination scenarios. The minimum flashover voltage and the dielectric strength for each insulator is measured and compared against each other. Based on the findings, considerations for appropriate insulator selection for ashy environments are discussed.

5.3 PREVIOUS STUDIES

This study builds on the preliminary research of Nellis and Hendrix, (1980) and Matsuoka et al. (1995). These pioneering studies have informed our experimental design and parameters.

Nellis and Hendrix (1980) carried out electrical tests on HVAC insulators which flashed over during the 1980 Mount St Helens eruption. A range of insulator types (115 kV, 500 kV jumper, 15 kV bus and switch) and configurations (suspension, strain, and vee-string) were removed from service, transported to a laboratory and subjected to a range of artificial wetting conditions (fog, light rain, and heavy rain) and ash thicknesses (3-6 mm). It was found that wet volcanic ash has a high probability of initiating flashovers when insulating surfaces (i.e. top and bottom of weathersheds) are completely coated in ash, and insulator profile and orientation are primary controls on pollution accumulation rates, and therefore performance. While their findings provide insight into the atmospheric and electrical conditions influencing ash-induced flashover, the study had some limitations: (1) the state of the insulators prior to ash-contamination (e.g. pre-existing contamination, dielectric strength, etc.) was unknown; (2) it was unclear whether the ash samples used in those tests had lost some of their soluble salt content (e.g. due to rain leaching) prior to analysis; (3) specific pollution severities (i.e. equivalent soluble/non-soluble deposit densities, (ESDD/NSDD)) were unspecified; and (4) no discussion or advice on optimal insulator selection for ashy environments was provided.

Matsuoka et al. (1995) collected ash samples from several Japanese volcanoes for chemical analyses and artificial pollution tests to assess the volcanic ash performance of a porcelain standard disc (250 mm diameter) suspension insulator and a porcelain long-rod model. The chemical and electrical properties (ESDD/NSDD) of each ash sample varied considerably, and increasing ash contamination severity significantly decreased the withstand voltage of the insulator specimens. The most significant finding was that volcanic ash did not reduce the performance of the suspension insulator as severely as sea-salt (ocean spray) contamination with equivalent ESDD. However, the long-rod specimen displayed withstand voltage characteristics almost equal to those found for sea-salt contamination, suggesting that differences in uniformity of the ash layer and wetting along the insulator surface were mainly responsible for the dissimilarity in results. While comparison against sea-salt contamination is a useful design exercise, the unusually high NSDD of volcanic ash makes it very different from other forms of airborne pollution (Chapters 1 and 4), and is expected to have additional implications for the flashover (or withstand) voltage characteristics of HV insulators. In addition, Matsuoka et al. (1995) analysed only 2 (ceramic) insulator models, did not provide flashover data past 0.2 mg/cm^2 ESDD (except for one outlier at 3 mg/cm^2), and did not specify important experimental design parameters such as ash contamination thickness, distribution, or coverage of protected creepage distance. This study therefore looks to complement existing knowledge on the flashover characteristics of HVAC suspension insulators through a comprehensive and methodical testing programme.

5.4 IMPORTANT FACTORS INFLUENCING POLLUTION-INDUCED FLASHOVER

This study investigates the main environmental, geological and electrical parameters most responsible for reducing the flashover voltage of HVAC insulators. The following sections provide rationale for our experimental design which has been adapted from those used in earlier volcanic ash studies (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995) and/or international technical standards (e.g. IEC 60507, 1991; IEEE Std 4, 1995).

5.4.1 Creepage and total surface area coverage

The single most important parameter of pollution performance in ceramic insulators is creepage distance (IEEE Std 1313.2, 1999). Nellis and Hendrix (1980) suggested that insulator strings and other types of external insulators with 30% or more of their creepage distance protected from/clear of ash contamination and rain would not initiate large-scale outages. The amount of creepage distance covered in wet volcanic ash should therefore be a primary control on the flashover voltage.

The distribution of the contaminant (i.e. the amount of surface area covered) has a significant influence on the flashover voltage of an insulator. Cherney et al. (1983) found that contaminating just the underside of standard-disc insulator weathersheds (higher surface area than the top surface) significantly lowered the flashover voltage from that observed with contamination applied only to the top surface. As with creepage coverage, the amount of surface area covered by volcanic ash is expected to be an important influence on the flashover characteristics of the insulators selected for this study.

5.4.2 Insulator profile, orientation, and material

The effect of the orientation of an insulator on its flashover performance is not subject to simple rules. Several factors affect the influence of insulator orientation on pollution performance (after IEC 60815-1, 2008):

1) Insulator profile and size;
2) Time taken for maximum pollution levels to build up;
3) Nature of the wetting process;
4) Flashover mechanism (e.g. surface flashover or intershed breakdown).

Nellis and Hendrix (1980) found that, of all orientations tested, the suspension (or 'I') configuration produced the lowest flashover voltage. Anecdotal field observations also suggest that HV suspension (vertical) insulators are more likely to flashover during or after ashfalls (e.g. Chapter 2), and are therefore considered most vulnerable. There have been some significant examples where this has not been the case, such as the 1995/96 eruption of Ruapehu (New Zealand), when several strain (horizontal) insulators located near the volcano (~15 km) flashed over from 3 mm of volcanic ash and mud contamination (Chapter 2). However, given the stronger evidence for the former situation, this study concentrates only on the effect of volcanic ash contamination on the flashover voltage of suspension insulators.

High-creepage insulators such as the fog or bowl-profiles generally perform better under polluted conditions (IEC 60815-1, 2008), however, large, deep ribs on the underside of these profiles can generate vortexes which may deposit high levels of pollution on portions of the insulator that are difficult to wash (Looms, 1988). Thus, despite the longer creepage path, a higher rate of pollution accumulation and greater rate of retention can degrade or even reverse the performance that was originally gained with extra creepage distance (Farzaneh and Chisholm, 2009).

Hydrocarbon and silicone greases, and room temperature vulcanising (RTV) coatings are widely used to improve the flashover performance of ceramic insulators situated in areas of high pollution as they surround contaminants with a monolayer of low-weight silicone polymers which imparts hydrophobicity to the pollution layer (Kim, 1990; Cherney and Gorur, 1999; Jia et al., 2008; Chapter 1). However, considering larger amounts of pollution may accumulate on some polymer surfaces than ceramics (IEC 60815-3, 2008; IEEE Std 1313.2, 1999) and contaminants with high non-soluble deposit density (NSDD) overwhelm the natural hydrophobicity transfer of silicone oils (Rizk et al., 1997), high levels of volcanic ash contamination (e.g. NSDD >100 mg/cm^2) may reduce the pollution performance advantage of polymers over comparable glass and porcelain designs.

5.4.3 Ash conductivity

Several factors influence the conductivity of volcanic ash (Chapter 3) (Figure 5.1). The conductivity of the ash layer will directly affect the amount of current flow across the insulator surface, and hence the likelihood of flashover. If the layer conductivity of a volcanic ash deposit on an HV insulator is sufficiently high, discharges are initiated, propagated and extinguished in a process called 'dry-band arcing'. If an arc grows to a sufficient length along the insulator, the remaining air gap will become too weak to withstand the line voltage and cause dielectric breakdown (flashover) across or around the surface of the insulator (Farzaneh and Chisholm, 2009). Results in Chapter 3 showed that the electrical conductivity of volcanic ash increases with increasing soluble salt content, moisture content, compaction (bulk density) and, to a lesser degree, particle size. These are important physical and chemical promoters of conductivity which are discussed further in Section 5.5.3.1.

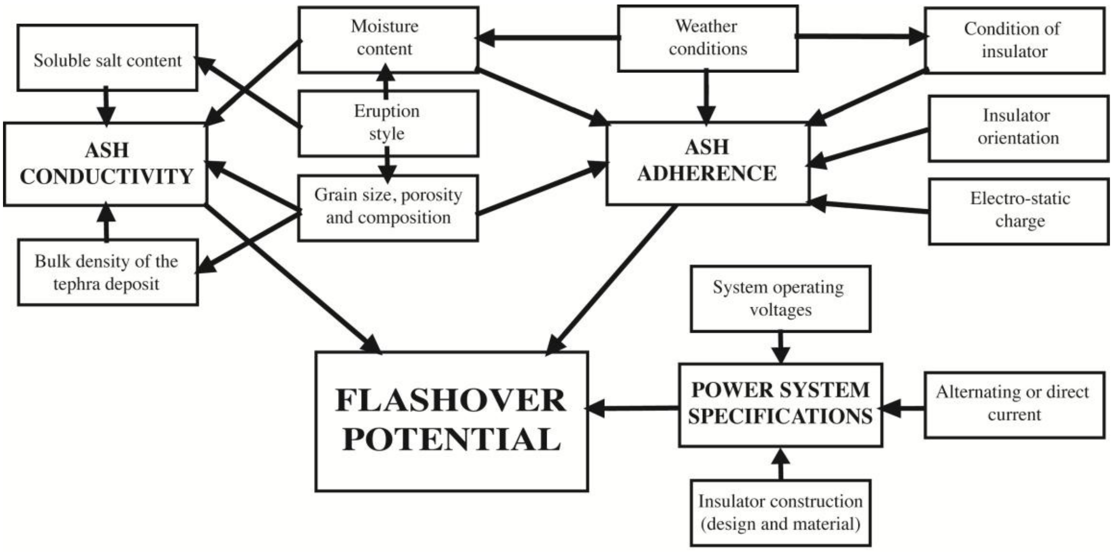

Figure 5.1: Flow chart illustrating the primary variables that promote volcanic ash-induced insulator flashover (adapted from Johnston, 1997).

5.5 METHODS

An electrical testing programme was designed to investigate how increasing ash-pollution severity would influence the flashover voltage of HVAC suspension insulators. The following sections describe the test facilities, insulators, testing procedures, and analytical methods used to assess the individual performance of each insulator specimen.

5.5.1 Test facilities

Clean-fog rapid flashover tests were performed in the HV laboratory at the University of Canterbury (UC). Voltage was supplied from 2 phases of a 3-phase 400 V supply to a 50 Hz, 400 V/300 kV, 100 kVA test transformer via a 400 V/0-440 V regulator as shown in Figure 5.2. The short circuit current at 300 kV rated voltage is 2.5 A. This is limited by the combination of the transformer series impedance and the impedance of the supply transformer, cable and regulator. Insulators were suspended and isolated from the ceiling of the HV laboratory. The top of the insulator string was earthed to replicate the configuration of insulators suspended from a transmission tower. To prevent unwanted corona discharge, the HV was applied to a copper sphere which was fastened to the base of the insulator via a cable from the test transformer.

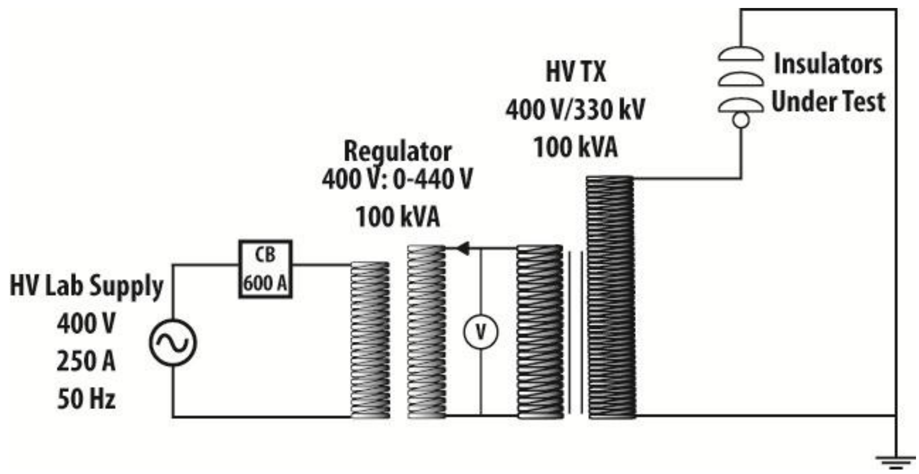

Figure 5.2: Schematic diagram of the test circuit.

Applied voltage across the insulator was measured with a rectifying transducer on the LV winding which supplied a meter on the control console. This was verified against an independent HV divider probe connected to the HV terminal up to 40 kV. The ratio between the voltage at the console meter and the voltage present at the HV divider was then used to calculate the applied voltage across the insulator.

5.5.2 Insulators

Considering the range of insulator designs used in a variety of polluted environments (IEC 60815-1, 2008), three ceramic (porcelain or glass) insulators of different profile and one non-ceramic (composite polymer) insulator, all commonly used in transmission systems in New Zealand, were chosen for analysis (Figure 5.3). Additionally, a standard glass insulator string was treated with a 0.5 mm layer of RTV silicone rubber coating provided by Hebei Silicone Valley Chemical Co. (China) according to the foam brush procedure prescribed by IEEE Std 1523 (2002) to investigate its effectiveness against volcanic ash contamination.

Table 5.1: Specifications for insulators used in this study.

Material	Profile	Insulator description	Figure	# units	# sheds	Shed diameter	Dry arc distance	Creepage distance
						mm		
Porcelain	Standard disc (clevis)	Cap and pin standard disc insulators are effective for use in areas with 'very light' to 'moderate' pollution severity, where a long creepage distance or modified profile is not required.	5.3a	3	3	240	617	1026
Toughened Glass	Standard disc (ball-and-socket)	The standard glass disc profile chosen for this study has deeper under-ribs than the porcelain unit, providing added protection from wetting.	5.3b	3	3	240	526	1035
Toughened Glass	Aeroform	Aeroform, aerodynamic or 'open profile' discs are typically used in heavily polluted regions such as deserts, industrial areas and/or coastal areas not directly exposed to salt spray. The aeroform profile is especially effective in arid environments and has very good self-cleaning properties.	5.3c	3	3	420	697	1191
Polymeric	66 kV long rod	Generally, polymer shed profiles are simpler than those of glass or porcelain and the majority can be classed as open profiles. However, the polymeric specimen used in this study has shallow (0.5 cm) under-ribs for increased protected creepage distance.	5.3d	1	6	170	700	1715
RTV Glass	Standard disc (ball-and-socket)	A RTV coating is applied to standard glass discs to create a hydrophobic surface. We wish to investigate the coating's effectiveness against volcanic ash contamination.	5.3e	3	3	240	526	1035

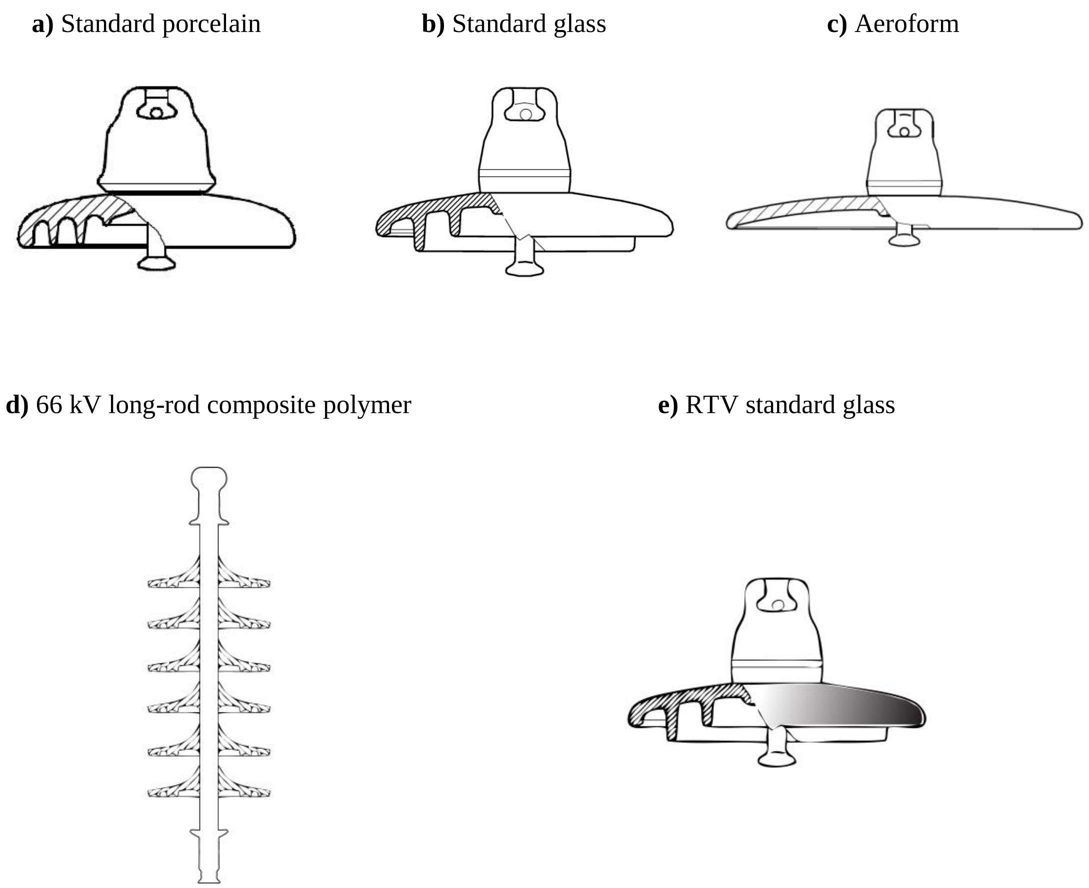

Figure 5.3: Insulator profiles for the 5 specimens selected for this study.

5.5.3 Procedures

5.5.3.1 Pseudo ash

While naturally occurring variations in volcanic ash properties may introduce additional effects on the flashover voltage of HV insulators, challenges in collecting pristine (e.g. unleached) samples and the large volume of material needed for artificial pollution tests made it logistically and practically difficult to collect freshly fallen ash for our analysis. Thus, using the method developed in Chapter 3, we bulk-manufactured a pseudo ash which replicates the chemical, physical and electrical parameters properties of freshly fallen ash. The replication of both soluble and non-soluble pollution for experimental use in the electrical industry is not uncommon. Kaolin, tonoko and bentonite (among others) mixed with a sodium chloride

(NaCl) solution have frequently been used in HV insulator contamination testing programmes (e.g. Fujitaka et al., 1968; Diesendorf and Parnell, 1974; Cherney et al., 1983; Gautum et al., 2006).

Results from Chapter 3 suggest that composition has little effect on the electrical conductivity of volcanic ash. Given the use of a basaltic proxy in both Chapters 3 and 4, and the large quantities readily available to us, unweathered Stoddart olivine basalt (from Halswell Quarry, Lyttelton volcano, New Zealand) (Guard, 1999) was maintained as the non-soluble volcanic component for our pseudo ash.

Cherney et al. (1983) showed that the particle size (up to 1 mm particle diameter) of non-soluble material has negligible influence on the flashover voltage of contaminated HV insulators. Similarly, Chapter 3 showed that all grain sizes can exhibit high conductivities when wet and are therefore similarly capable of inducing insulator flashover. To examine whether the particle size of volcanic ash has any effect on the flashover voltage of HV insulators, we chose to create two different pseudo ashes: (1) a predominantly fine-grained fraction (<0.1 mm) and (2) an ash with a coarse-grained component (<1 mm). These were manufactured by dry sieving the original crushed and pulverised product. Particle size distributions for both pseudo ashes were determined using a HORIBA Partica LA-950 laser diffraction particle size analyser. Each pseudo ash was sampled twice and measured a minimum of five times in the particle size analyser to ensure reliability of the results. The output values were averaged and the distribution curves are shown in Figure 5.4.

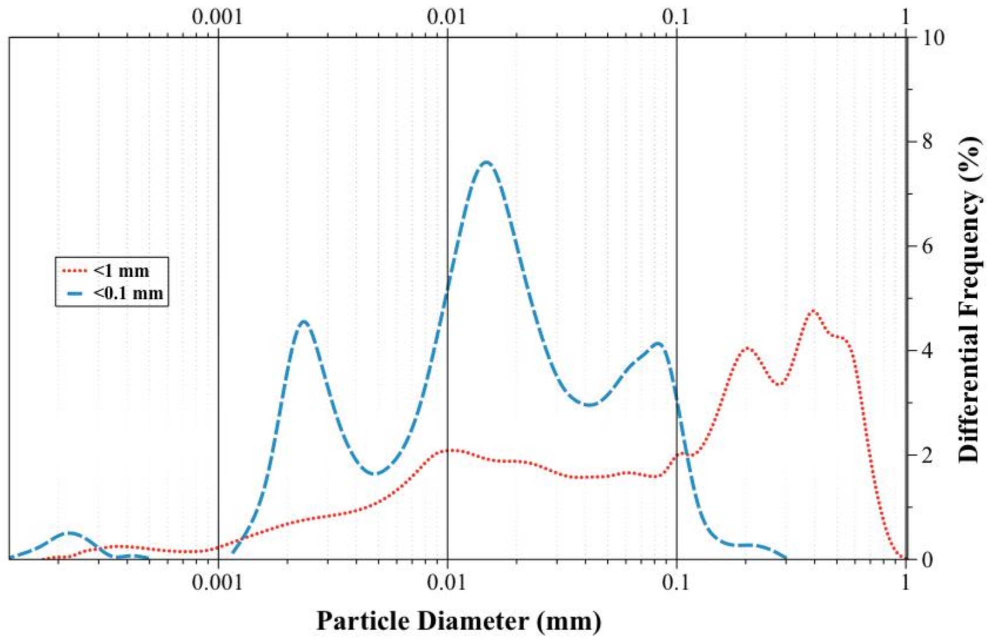

Figure 5.4: Particle size distributions for the 2-pseudo ashes used in this study (adapted from Chapter 4).

To replicate the interactions at the ash–gas interface and other processes occurring between ash and volatiles within a volcanic plume, the simplified chemical dosing method developed in Chapter 3 was used to produce soluble salts on the surfaces of the pseudo ash. ESDD values of pseudo ash in Chapter 4 showed that a 0.15 M NaCl salt solution added to a 3:1 ratio of ash:brine will create an ash with electrical properties which are within the bounds of freshly fallen ash (e.g. resistivity values between 200 and 1,000 Ωm for uncompacted deposits (Chapter 3)). Thus, this concentration was used as an appropriate dosing agent for our artificial pollution tests.

5.5.3.2 Application of the pollution layer

Standardised artificial pollution tests recommend applying pollution via the flow-on or dipping techniques (IEC 60507, 1991; IEEE Std 4, 1995). However, considering (1) the importance of retaining soluble surface salts inherent in freshly fallen volcanic ash, (2) the potential for volcanic ash to be deposited in large quantities (e.g. >10 mm thicknesses) and (3) the lack of appropriate testing standards pertinent to volcanic ash contamination, the pollution layer for electrical tests was applied using dry pseudo ash. Prior studies (e.g.

Nellis and Hendrix, 1980; Matsuoka et al., 1995) also found that this method produces a realistic representation of contamination observed in the field.

Eruption plumes are dispersed by prevailing winds and volcanic ash can be deposited hundreds to thousands of kilometres from the volcano, depending on wind strength, ash grain size, ash density, and eruption magnitude (Sparks, 1986). Thus, 9 different ash-contamination scenarios (Table 5.2) were devised and replicated based on the depositional patterns described in existing literature (e.g. Nellis and Hendrix, 1980; Blong, 1984; Chapter 2) and observations made in the field (e.g. Appendices 2 and 3). Contaminated scenarios (described herein as scenarios 4-9) are representative of worst-cases, as the entire top and/or bottom surfaces were coated as uniformly as possible. Given the lab setting, no wind or breeze was present during electrical tests.

Table 5.2: The 9 different contamination scenarios devised for this study.

Scenario	Replicated environment	Wetting rate (mm/hr)	Ash top (mm)	Ash bottom (mm)	Particle size (mm)
1	Clean insulator in a dry environment	0	0	0	N/A
2	Light contamination in a dry environment	0	1	0	<0.1 or <1
3	Clean insulator in a wet environment	6	0	0	N/A
4	Light contamination in a wet environment	6	1	0	<0.1
5	Light contamination in a wet environment	6	1	0	<1
6	Moderate contamination in a wet environment	6	3	0	<0.1
7	Moderate contamination in a wet environment	6	3	0	<1
8	Heavy contamination in a wet environment	6	6	1	<0.1
9	Heavy contamination in a wet environment	6	6	1	<1

For scenarios 2 and 4 – 9, dry ash was applied to the top of insulator weathersheds using a small sieve (diameter 10 cm, mesh size <0.1 or <1 mm). For scenarios 8 and 9, dry ash was applied to the bottom surface of weathersheds by first spraying the insulator with a fine mist of water (same water source as that used for light rain simulation discussed in Section 5.5.3.3) and then dusting pre-sieved ash over the surface by hand. By alternating between misting and dusting, a relatively uniform ash layer of 1-2 mm was attained (Figure 5.5).

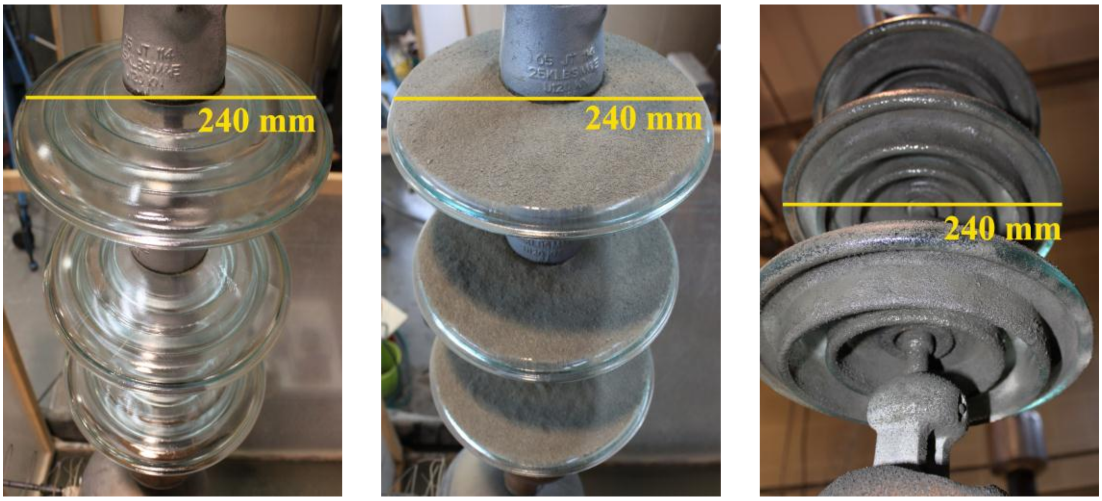

Figure 5.5: Standard glass insulator specimen before running electric tests for **a)** scenario 1, **b)** scenario 4, and **c)** scenario 9, (see Table 5.2 for scenarios).

IEC 60815-1 (2008) suggests that type A pollution (that with a non-soluble component) such as volcanic ash is best characterised by ESDD/NSDD measurements. Similarly, artificial pollution tests most often use ESDD as a comparative indicator of pollution severity. Thus, this study uses ESDD as the common measure of pollution severity for insulator performance curves. To broaden this focus, we also consider other important hazard intensity parameters such as ash thickness, NSDD, and % surface area and/or creepage coverage. ESDD and NSDD for each scenario (top surface, bottom surface and an average of both) were calculated using the pseudo ash data presented in Chapter 4.

5.5.3.3 Artificial wetting process

Earlier studies suggest dry volcanic ash is non-conducting and will not immediately lead to insulator flashover (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995; Chapters 2 and 3). Thus, an artificial wetting process was assembled to simulate humid climatic conditions.

Light wetting conditions such as fog, dew, or drizzle are primarily responsible for pollution-related flashovers (e.g. IEC 60815-1, 2008; Baker et al., 2009). This is supported by Nellis and Hendrix (1980) and ample accounts of volcanic ash-induced flashovers from the field (Chapter 2). However, Matsuoka et al. (1995) found that, among the various wetting conditions, the withstand voltage of insulators contaminated by volcanic ash was lowest under simulated heavy rain (e.g. >10 mm/hr). Considering the importance of retaining ash on the insulator for the duration of flashover tests (i.e. to ensure the conductive ash layer does not get washed away), and the common use of simulated mist, steam or fog for standardised artificial pollution tests (e.g. IEC 60507, 1991; IEEE Std 4, 1995), light-moderate rain conditions (~6 mm/hr) were replicated using an air atomising nozzle (Figure 5.6). The spray nozzle used for the artificial wetting process was configured perpendicular to the test insulators, according to the guidelines prescribed by IEC 60507 (1991) and IEEE Std 4 (1995).

Atmospheric conditions such as temperature (e.g. Ishii et al., 1984; Zaengl et al., 1991) and barometric pressure (e.g. Rudakova and Tikhodeev, 1989; Hoch and Swift, 1992) have an influence on the flashover voltage of HV insulators (Mizuno et al., 1997). Thus, ambient (laboratory) temperature and barometric pressure were recorded at the beginning of each testing round to account for any major variations in flashover voltage. These results are presented in Section 5.6.

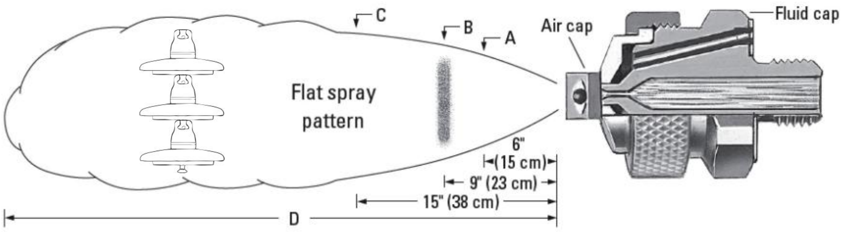

Figure 5.6: Top: A contaminated composite insulator being subjected to light rain during electrical tests, **Bottom:** External air + water mixing atomising spray nozzle (not to scale) used during the rapid flashover experiments. The insulator specimen was positioned in a vertical (string) position, within the atomised rain cloud, approximately 2 m (midway between distances C and D) from the nozzle.

Similarly, temperature and conductivity of the simulated rain source (Christchurch, New Zealand tap water with a volume conductivity ~130 μS/cm) varied slightly over the course of the testing programme. To account for these changes, 3 temperature and 3 conductivity measurements were taken, averaged and recorded before starting each scenario. These results can also be found in Section 5.6.

5.5.3.4 Data analysis

Clean-fog rapid flashover method

Experimental determination of the flashover voltage for different insulator profiles covering a wide range of contaminated conditions is extremely time consuming (Sundararajan and Gorur, 1996). The standardised solid layer artificial pollution test uses an 'up and down' method to statistically determine the 50% flashover voltage (V_{50}) of the insulator being tested (IEC 60507, 1991; IEEE Std 4, 1995). To acquire a robust and extensive dataset in a reasonable space of time, we adapted the clean-fog rapid flashover method first developed by Lambeth (1988) to determine the V_{50} of specimen insulators. The clean fog rapid flashover method follows a preparation procedure identical to that of standard pollution tests, but varies the applied voltage upwards or downwards in relatively small steps (e.g. 4-5%) to calculate V_{50} over an elapsed period of artificial wetting. Using the rapid flashover method, the V_{50} at a given pollution level (ash thickness and/or ESDD/NSDD) can be estimated in 1-2 hrs time. Results obtained from previous application of the rapid flashover method (e.g. Lambeth, 1988; Vlastos et al., 1991; Gutman et al., 2012) have shown good correlation with those reported in standard up and down tests. Thus, electrical tests were carried out according to the following procedure (adapted from Lambeth, 1988):

1. Install clean insulator in the configuration and location to be used for testing;
2. Contaminate insulator in place with dry pseudo ash to desired thickness (ESDD/NSDD) and surface coverage;
3. Preliminary tests discovered static-repellence of dry ash deposits with increasing applied voltage (Wardman et al., 2010; Mee et al., 2012). To avoid this self-cleaning effect or dielectrophoresis (Pohl, 1978), turn on light rain for 5 minutes to wet the ash layer before energisation;
4. Energise insulators to desired 50 Hz voltage level;
5. At constant 50 Hz voltage level, continue testing for 2 minutes or until flashover occurs;
6. If no flashover occurs, raise voltage in 5% steps every 2 minutes until flashover;
7. If a flashover occurs, re-energise the insulator at a voltage ~2.5 steps below the last flashover value;
8. This sequence is repeated for each scenario, with the flashover voltage values decreasing to a minimum during the period of maximum wetness (maximum conductivity). A round of tests may

stop once flashover values are consistently above the minimum or until 15 consecutive flashovers have been recorded.

To ensure repeatability and reliability of results, three rounds of tests were performed per scenario. The series of flashover values should produce a U-shaped pollution performance curve, corresponding to the reduction of flashover voltage as attached soluble salts are dissolved from the ash and recovery as the electrolytic solution is washed off the insulator surface (e.g. Lambeth, 1988; Vlastos et al., 1991; Gutman et al., 2012).

Rapid flashover method for composite insulators

There are currently no standardised testing methods for polymer insulators (IEC 60815-3, 2008). Early artificial pollution tests for composite insulators found that polymeric surfaces tend to lose some of their hydrophobicity with each flashover; however, new insight suggests composite insulators are very rarely completely hydrophobic (or completely hydrophilic) in service (Farzaneh and Chisholm, 2009). The rapid flashover test therefore allows any potential pollution performance reduction due to loss of hydrophobicity to be detected and evaluated (Gutman et al., 2012).

5.5.3.5 Determination of minimum flashover voltage and dielectric strength

The performance criterion for the rapid flashover technique is the minimum flashover voltage value (V_{min}). The V_{min} can be determined in one of two ways: (1) if wetting time is short, the lowest flashover value may be used (Lambeth, 1988), or (2) to account for the random variation in flashover values, it is acceptable to use an average of the lowest flashover and the highest withstand values obtained during the 3 test rounds as the V_{min} for the entire scenario (Gutman et al., 2012).

Limitations in the voltage capacity of our testing transformer meant that each ceramic insulator string was limited to 3 units (discs). No transmission or distribution lines in New Zealand utilise 3-disc suspension insulators, thus, it is not possible to compare V_{min} values obtained from this study to normal operating (service) voltages. However, V_{min} data obtained from rapid flashover tests are usually presented in terms of V_{50} (IEEE Working Group, 1979), which is an indication of the insulator's dielectric strength (CIGRE Working Group 33.07, 1992). As a general rule, if the ratio of creepage distance to dry arc distance is not too large, clean fog test results tend to be linear with regard to the number of insulators in a string and, hence, to the creepage and dry arc distances (IEEE Std 1313.2, 1999). It is therefore common to express test results as a critical flashover gradient (V_{50}), where the flashover stress (V_{min}) is normalised to creepage distance (in units of kV rms of line-to-earth voltage per metre (kV/m) or unit (kV/unit) creepage distance). This corrects for much of the performance difference between insulators of different profiles (Farzaneh and Chisholm, 2009).

5.6 RESULTS

Raw flashover data and averages of the results from the three rounds of tests per scenario are provided for each insulator type in the following sections (Figures 5.7-5.11, Tables 5.3-5.7).

5.6.1 Standard porcelain

The V_{50} of the standard porcelain insulator increased by 5% from scenario 1 to scenario 2 (i.e. with the addition of dry volcanic ash to a dry insulator) (Table 5.3). There was a 12% reduction in V_{50} from scenario 3 to 4 and dielectric strength for scenarios 4-7 ranged from 93-102 kV/m. Scenarios 4 and 6 (pseudo ash <0.1 mm particle diameter) displayed a 5% reduction in V_{50} while scenarios 5 and 7 (pseudo ash <1 mm particle diameter) showed no difference in V_{50} despite an increase in pollution severities (ESDD/NSDD). Scenarios 8 and 9 had the highest ESDD/NSDD and surface coverage of all scenarios and also displayed the lowest V_{50} values, with scenario 9 (pseudo ash <1 mm particle diameter) exhibiting the lowest (36 kV/m) of all scenarios.

Table 5.3: Test results for the standard porcelain insulator.

		SCENARIO								
		1	2	3	4	5	6	7	8	9
Grain Size	mm		<1		<0.1	<1	<0.1	<1	<0.1	<1
Thickness (Top)	mm		1		1	1	3	3	6	6
$ESDD_t$	mg/cm^2		0.1		0.1	0.1	0.6	0.6	1.1	1.2
$NSDD_t$	mg/cm^2		44.4		35.3	44.4	185	247	359	447
Thickness (Btm)	mm								1	1
$ESDD_b$	mg/cm^2								0.1	0.1
$NSDD_b$	mg/cm^2								35.3	44.4
Ave. ESDD	mg/cm^2		0.02		0.02	0.02	0.1	0.1	0.3	0.4
Ave. NSDD	mg/cm^2		10.7		8.5	10.7	44.7	59.6	113	142
Surface Cover	%		24		24	24	24	24	100	100
Rain Conductivity	µS/cm			128	133	117	113	108	127	107
Lab Temp	°C	13.5	14.0	17.5	14.0	16.3	16.0	14.8	14.7	16.0
Baro. Pressure	hPa	1010	1015	1005	1014	1018	1020	998	1003	1010
Hi Withstand	kV	170	180	120	105	95	100	95	45	35
Lo Flashover	kV	180	190	125	110	100	105	100	49	38
V_{min}	kV	175	185	123	108	98	103	98	47	36
V_{50}	kV/m	165.7	175.4	117.0	102.3	92.6	97.5	92.6	43.9	34.1

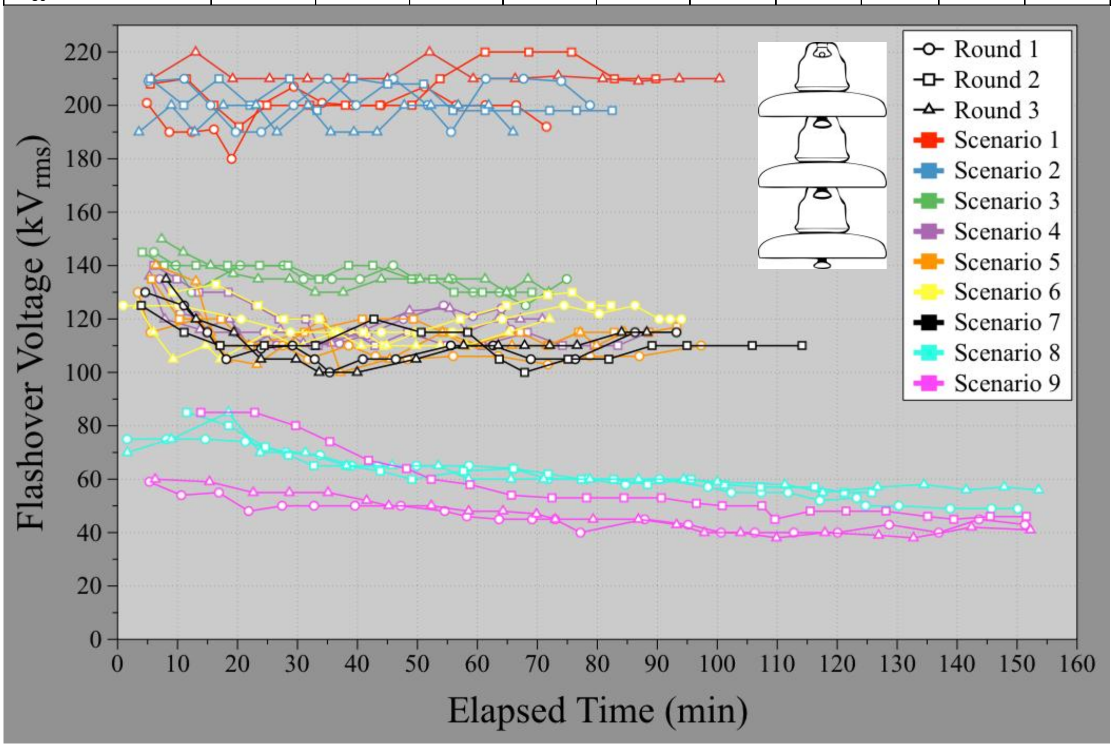

Figure 5.7: Flashover voltages for the standard porcelain insulator during scenarios 1-9.

5.6.2 Standard glass

The V_{50} of the standard glass insulator increased by 3% from scenario 1 to scenario 2 and decreased by 9% from scenario 3 to scenario 4. Modest reductions in V_{50} were observed from scenario 4 to scenario 6 (5%) and from scenario 5 to scenario 7 (2%). A 100/148% increase in ESDD/NSDD from scenario 6 to 8, caused a 60% reduction in V_{50}. Similarly, an ESDD/NSDD increase of 100/131% between scenarios 7 and 9 caused a 73% reduction in V_{50}. The lowest dielectric strength displayed by the standard glass insulator was during scenario 9 (30 kV/m) and was the lowest V_{50} value observed over the testing programme.

Table 5.4: Test results for the standard glass insulator.

		SCENARIO								
		1	2	3	4	5	6	7	8	9
Grain Size	mm		<0.1		<0.1	<1	<0.1	<1	<0.1	<1
Thickness (Top)	mm		1		1	1	3	3	6	6
$ESDD_t$	mg/cm^2		0.1		0.1	0.1	0.6	0.6	1.1	1.2
$NSDD_t$	mg/cm^2		44.4		35.3	44.4	185	247	359	447
Thickness (Btm)	mm								1	1
$ESDD_b$	mg/cm^2								0.1	0.1
$NSDD_b$	mg/cm^2								35.3	44.4
Ave. ESDD	mg/cm^2		0.03		0.03	0.03	0.2	0.2	0.4	0.4
Ave. NSDD	mg/cm^2		11.8		9.4	11.8	49.3	65.9	122	152
Surface Cover	%		27		27	27	27	27	100	100
Rain Conductivity	μS/cm			135	144	141	137	141	148	143
Lab Temp	°C	12.3	12.7	13.2	16.0	17.7	17.3	17.2	16.7	16.2
Baro. Pressure	hPa	1030	1028	1027	1022	1013	1010	1020	1014	1018
Hi Withstand	kV	165	170	110	100	110	95	110	45	30
Lo Flashover	kV	170	175	115	105	115	100	111	47	30
V_{min}	kV	168	173	113	103	113	98	111	46	30
V_{50}	kV/m	159.4	164.3	106.3	96.6	106.3	91.8	106.3	43.5	29.0

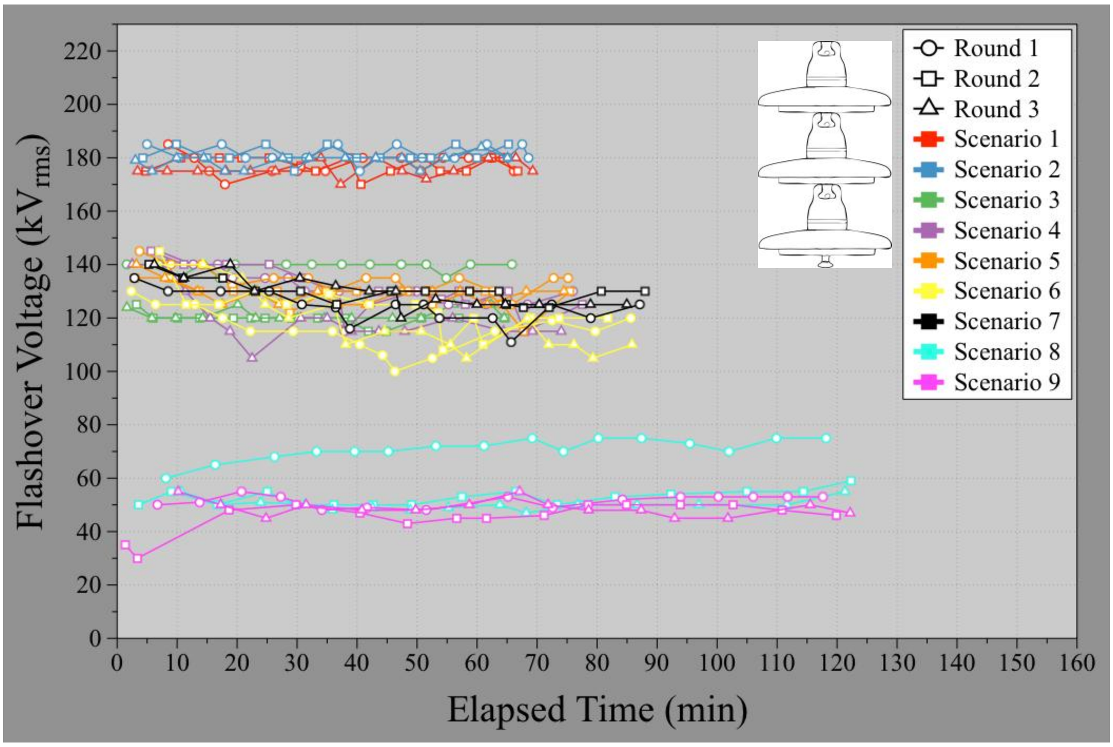

Figure 5.8: Flashover voltages for the standard glass insulator during scenarios 1-9.

5.6.3 Aeroform

The V_{50} of the aeroform insulator remained the same from scenario 1 to scenario 2 but decreased by 33% from scenario 3 to scenario 4. A 12% increase in V_{50} was observed between scenario 4 and scenario 6 despite higher pollution severity in the latter. Contrarily, the 400/557% increase in ESDD/NSDD from scenario 5 to scenario 7 caused a modest 3% reduction in V_{50}. From scenario 6 to 8, the V_{50} was reduced by 53% and by 55% from scenario 7 to 9. The lowest dielectric strength observed for the aeroform insulator was during scenario 9 (34 kV/m).

Table 5.5: Test results for the aeroform insulator.

		SCENARIO								
		1	2	3	4	5	6	7	8	9
Grain Size	mm		<1		<0.1	<1	<0.1	<1	<0.1	<1
Thickness (Top)	mm		1		1	1	3	3	6	6
$ESDD_t$	mg/cm^2		0.1		0.1	0.1	0.6	0.6	1.1	1.2
$NSDD_t$	mg/cm^2		44.4		35.3	44.4	185	247	359	447
Thickness (Btm)	mm								1	1
$ESDD_b$	mg/cm^2								0.1	0.1
$NSDD_b$	mg/cm^2								35.3	44.4
Ave. ESDD	mg/cm^2		0.04		0.04	0.04	0.2	0.2	0.5	0.5
Ave. NSDD	mg/cm^2		17.9		14.2	17.9	74.7	99.7	166	207
Surface Cover	%		43		43	43	43	43	100	100
Rain Conductivity	µS/cm			140	130	119	142	125	124	128
Lab Temp	°C	18.0	17.5	17.2	16.7	13.7	14.8	14.8	15.2	12.7
Baro. Pressure	hPa	1006	999	1004	989	1009	1001	1002	999	1003
Hi Withstand	kV	155	155	125	85	95	95	90	45	40
Lo Flashover	kV	160	160	130	88	98	100	95	47	43
V_{min}	kV	158	158	128	86	96	98	93	46	42
V_{50}	kV/m	130.1	130.1	105.0	71.4	79.8	79.8	75.6	37.8	33.6

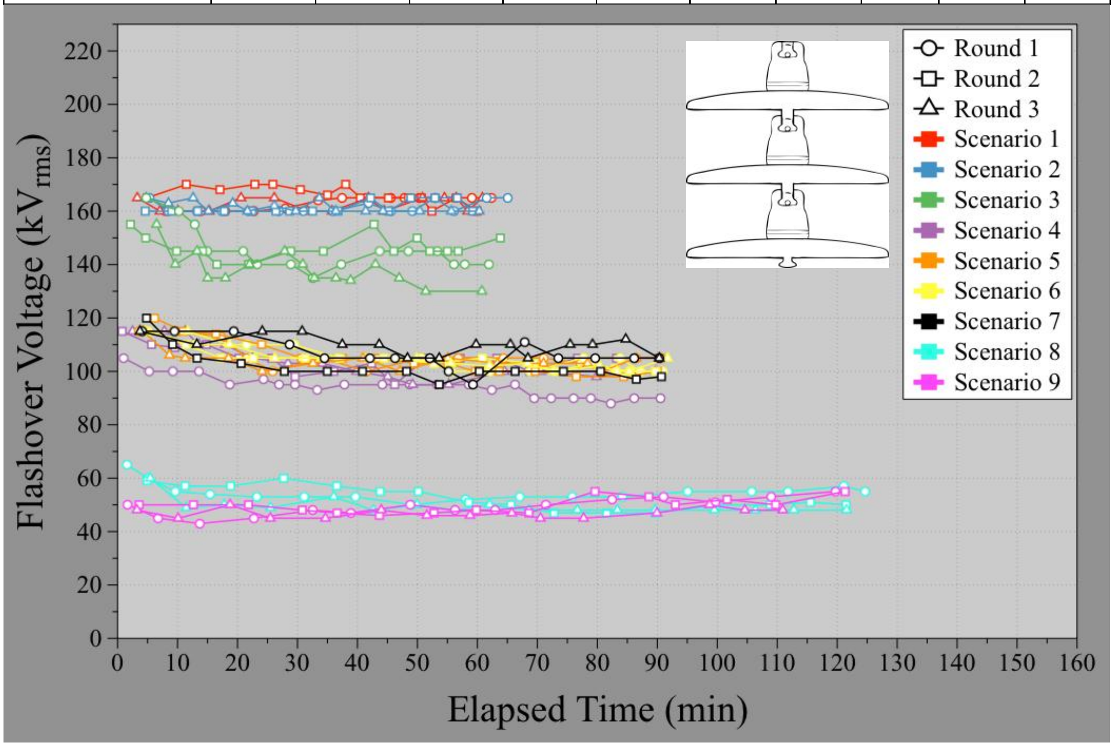

Figure 5.9: Flashover voltages for the aeroform insulator during scenario 1-9.

5.6.4 66 kV long-rod composite polymer

The V_{50} of the composite insulator increased by 1% from scenario 1 to scenario 2 and decreased by 5% from scenario 3 to scenario 4. Scenario 5 saw a 7% decrease in V_{50} from scenario 3 while scenarios 6 and 7 caused 26%

and 16% reductions in V_{50}, respectively. Scenarios 8 and 9 produced the most critical V_{50} values, with 66% and 67% reductions from scenario 3, respectively. The composite insulator had the highest ESDD/NSDD values across all contaminated scenario.

Table 5.6: Test results for the polymeric insulator.

		SCENARIO								
		1	2	3	4	5	6	7	8	9
Grain Size	mm		<0.1		<0.1	<1	<0.1	<1	<0.1	<1
Thickness (Top)	mm		1		1	1	3	3	6	6
$ESDD_t$	mg/cm^2		0.1		0.1	0.1	0.6	0.6	1.1	1.2
$NSDD_t$	mg/cm^2		44.4		35.3	44.4	185	247	359	447
Thickness (Btm)	mm								1	1
$ESDD_b$	mg/cm^2								0.1	0.1
$NSDD_b$	mg/cm^2								35.3	44.4
Ave. ESDD	mg/cm^2		0.04		0.04	0.04	0.3	0.3	0.5	0.6
Ave. NSDD	mg/cm^2		19.1		15.2	19.1	79.6	106	174	218
Surface Cover	%		32		32	32	32	32	100	100
Rain Conductivity	µS/cm			125	120	128	124	134	136	137
Lab Temp	°C	19.8	15.0	15.5	15.2	16.7	13.0	16.3	18.0	18.0
Baro. Pressure	hPa	996	989	1004	1002	993	1002	1013	1002	1003
Hi Withstand	kV	205	205	190	180	175	140	160	65	60
Lo Flashover	kV	207	210	195	185	180	145	165	68	65
V_{min}	kV	206	208	193	183	178	143	163	66	63
V_{50}	kV/m	119.5	119.5	110.8	105.0	102.0	81.6	93.3	37.9	35.0

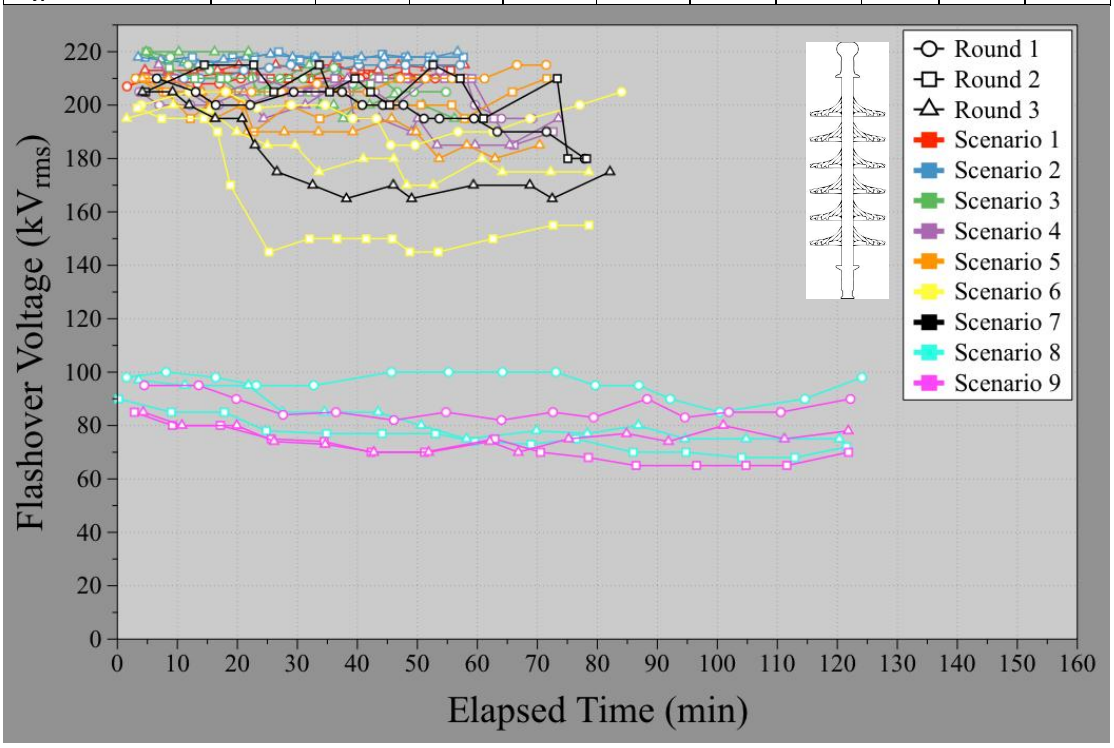

Figure 5.10: Flashover voltages for the polymeric insulator during scenario 1-9.

5.6.5 RTV standard glass

There was no change in V_{50} from scenario 1 to 2. Scenario 3 brought about a 27% reduction in V_{50} from the dry scenarios (1 and 2), while scenarios 4 and 5 saw a further 13% reduction. A 100/148% increase in ESDD/NSDD from scenario 6 to 8, caused a 62% reduction in the V_{50}. Similarly, an ESDD/NSDD increase of 100/131% between scenario 7 and 9 caused a 65% reduction in the V_{50}. The RTV insulator exhibited the highest V50 values for scenario 1 and scenarios 3-6. Its lowest dielectric strength was observed during scenario 9 (33.8 kV/m).

Compared with data acquired for the untreated standard glass insulator, the RTV coated specimen exhibited better pollution performance for scenarios 1-4. The V_{50} was equivalent for scenario 5 while the unmodified insulator displayed higher dielectric strength than the RTV coated specimen under heavier contamination levels in scenarios 6-8.

Table 5.7: Test results for the RTV glass insulator.

		SCENARIO								
		1	2	3	4	5	6	7	8	9
Grain Size	mm		<1		<0.1	<1	<0.1	<1	<0.1	<1
Thickness (Top)	mm		1		1	1	3	3	6	6
$ESDD_t$	mg/cm^2		0.1		0.1	0.1	0.6	0.6	1.1	1.2
$NSDD_t$	mg/cm^2		44.4		35.3	44.4	185	247	359	447
Thickness (Btm)	mm								1	1
$ESDD_b$	mg/cm^2								0.1	0.1
$NSDD_b$	mg/cm^2								35.3	44.4
Ave. ESDD	mg/cm^2		0.03		0.03	0.03	0.2	0.2	0.4	0.4
Ave. NSDD	mg/cm^2		11.8		9.4	11.8	49.3	65.9	122	152
Surface Cover	%		27		27	27	27	27	100	100
Rain Conductivity	μS/cm			131	127	134	133	142	143	126
Lab Temp	°C	19.7	18.7	19.7	19.0	16.2	17.5	19.5	17.7	18.2
Baro. Pressure	hPa	1013	1013	1011	1009	1025	1026	1024	1015	1012
Hi Withstand	kV	175	175	130	110	110	105	100	40	35
Lo Flashover	kV	180	180	130	115	115	110	105	42	40
V_{min}	kV	178	178	130	113	113	108	103	41	38
V_{50}	kV/m	169.1	169.1	125.6	106.3	106.3	101.4	96.6	38.6	33.8

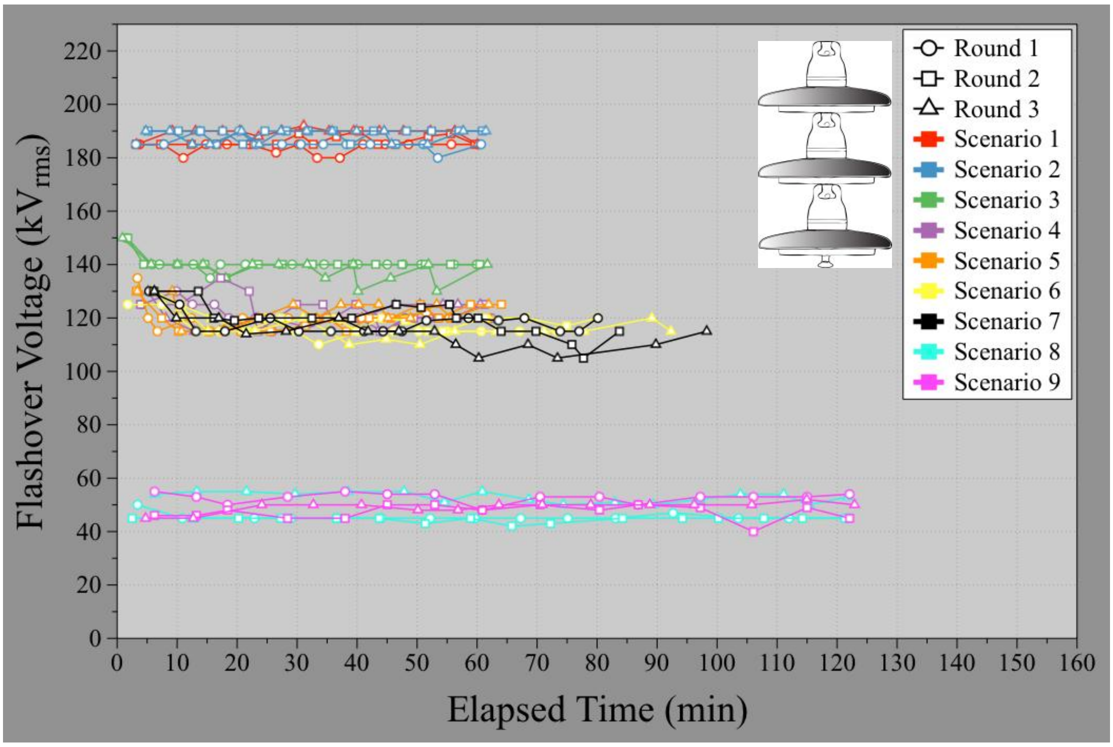

Figure 5.11: Flashover voltages for the RTV glass insulator during scenarios 1-9.

5.7 DISCUSSION

Critical flashover voltages were only observed once top and bottom surfaces of insulator weathersheds were completely covered in ash. This suggests that significant deposits of ash must accumulate on the bottom surface of suspension insulators before flashover will occur in-service. The following sections (1) compare and discuss the pollution performance of the ceramic and non-ceramic insulators used in this study, (2) consider the most influential environmental, volcanological and electrical parameters on the flashover voltage, (3) provide comment on important insulator selection criteria for ashy environments.

5.7.1 Pollution performance

Trends in the plotted V_{50} data and associated lines of best fit indicate that the dielectric strength of the 5 insulators decreased with increasing pollution severity (ESDD/NSDD and/or ash thickness) (Figure 5.12).

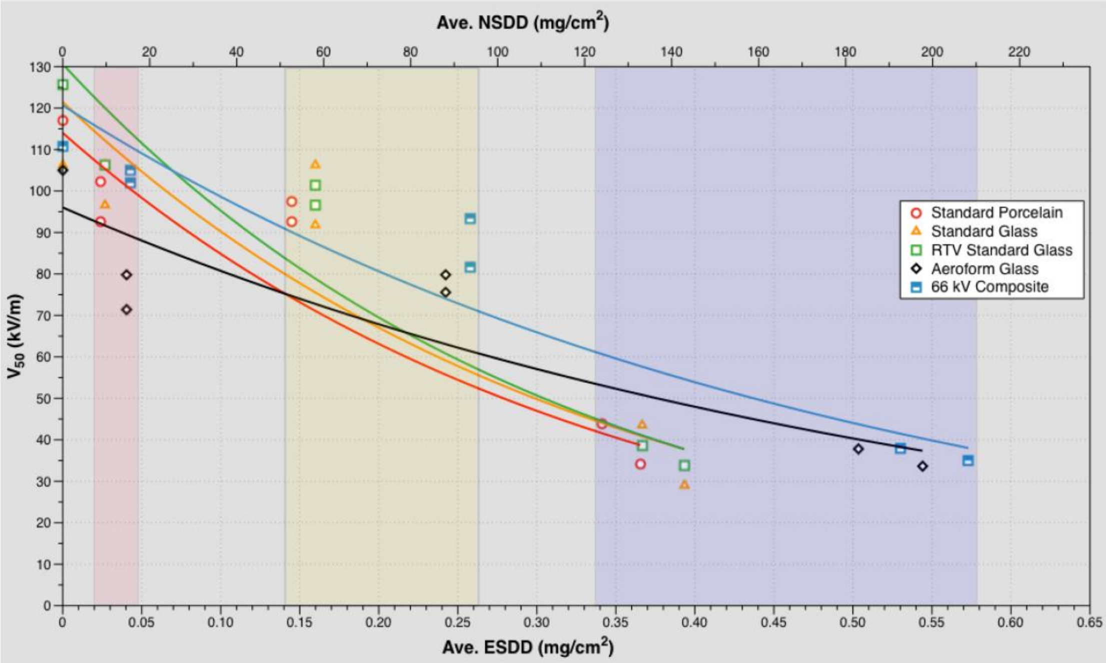

Figure 5.12: Pollution performance curves for scenarios 3-9. The Red shaded area represents the range of average ESDD/NSDD values for scenarios 4 and 5 (Ave. ESDD/NSDD 0.02/10.7 – 0.04/19.1 mg/cm^2; 1 mm thicknesses on top surface); yellow represents those for scenarios 6 and 7 (Ave. ESDD/NSDD 0.1/60 – 0.3/106 mg/cm^2; 3 mm thicknesses on top surface); blue for scenarios 8 and 9 (ESDD/NSDD 0.3/113 – 0.6/218 mg/cm^2; 6 mm and 1 mm on top and bottom surfaces, respectively).

Performance curves for the porcelain, glass and RTV insulators are similar and may be explained by their comparable dimensions (e.g. creepage length, dry arc/connection length, and shed diameter), which, in turn, produce similar pollution (ESDD/NSDD) severities.

Despite significantly higher ESDD values, the aeroform and composite insulators displayed equivalent dielectric strength to that of other models during the most critical scenarios (8 and 9). This suggests (1) insulators tested in this study have similar potential to flashover at rated line voltage during critically contaminated conditions (i.e. both top and bottom surfaces of sheds coated in wet ash), and (2) increasing contamination severity (i.e. thickness and/or ESDD/NSDD) has little effect on dielectric strength once the top and bottom surfaces of the insulator have been coated by ≥1 mm of ash.

For the majority of insulators, there was little (e.g. <10%) to no change in V_{50} for scenarios 4-7. This suggests that moderate accumulations of volcanic ash can accumulate on the top surfaces of insulator sheds (up to 3 mm in this study) without severely reducing dielectric strength, provided the bottom surface of the insulator remains clean and dry. This is important, as in a low wind setting volcanic ash will most readily accumulate on the top of horizontal surfaces.

5.7.1.1 Ceramic insulators

Ceramic insulators used herein generally showed higher dielectric strength than those in Matsuoka et al. (1995) under light to heavy pollution severities (ESDD from 0.001 to 0.2 mg/cm^2) (Figure 5.13). However, above this threshold, all known volcanic ash-flashover studies show similar performance data, with critical V_{50} values being ~10 kV/unit (Table 5.8).

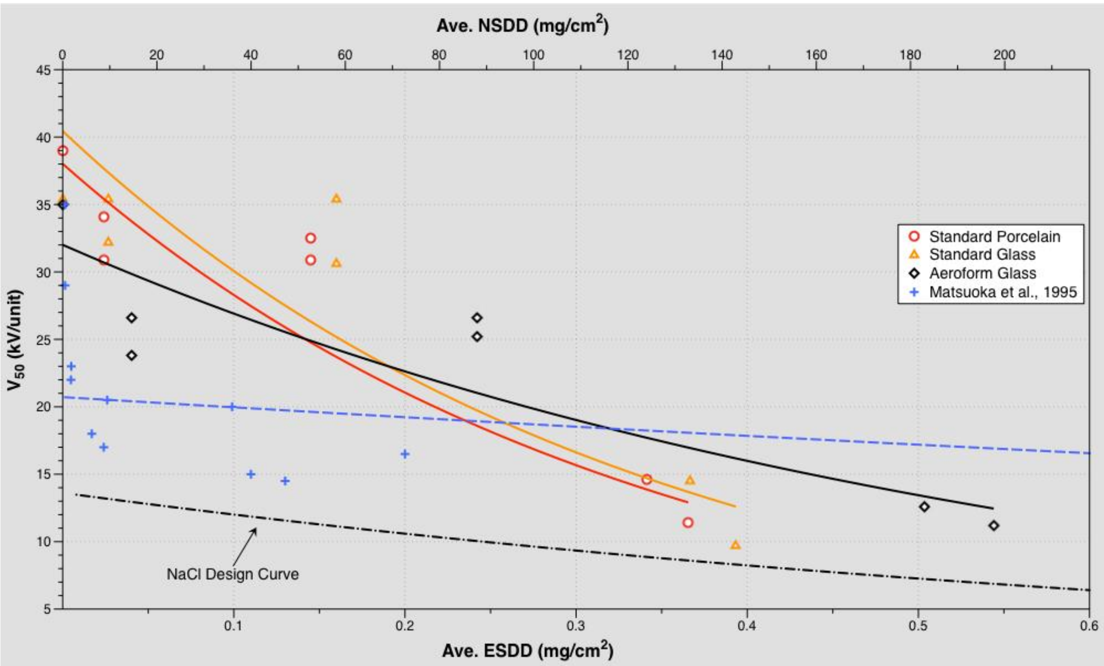

Figure 5.13: V_{50} (kV/unit) values for the ceramic insulators used in this study (scenarios 3-9). The NaCl design curve and volcanic ash data from Matsuoka et al. (1995) have been added for comparison.

With the exception of scenario 9, the aeroform insulator consistently displayed the lowest dielectric strength of all designs during contaminated scenarios. This is likely due to the reduced creepage distance on the underside of the insulator. As creepage distance is proportional to pollution performance, the relatively low performance of the aeroform specimen is likely due to a balanced distribution of creepage distance over the top and bottom surfaces. Despite an absence of corrugation and 30-60% improvement in self-cleaning ability over the standard disc insulator (Akbar and Zedan, 1991), results in this study suggest that aeroform suspension insulators will not perform as well as standard disc profiles in ashy environments. However, the improved self-cleaning ability may be advantageous in the horizontal configuration, though more research is needed to investigate this.

Table 5.8: Comparison of volcanic ash pollution performance results for three studies on standard ceramic suspension insulators.

Lab	Investigators	Year	# of Units/ discs	Insulator Profile and Material	Lowest V_{50} (kV/unit)	ESDD (mg/cm^2)
BPA	Nellis & Hendrix	1980	6	Std Porcelain	11	0.3-0.6
NGK	Matsuoka et al.	1995	4	Std Porcelain	8*	3
UC	Wardman et al.	2013	3	Std Porcelain	11	0.4
UC	Wardman et al.	2013	3	Std Glass	10	0.4
UC	Wardman et al.	2013	3	Aeroform Glass	11	0.5

*Estimation of V_{50} based on lowest withstand value of 7 kV/unit.

5.7.1.2 Non-ceramic insulators

The composite long-rod model most consistently displayed the highest dielectric strength of all insulators. As this specimen is rated for a 66 kV system, its single-phase operating voltage is ~38 kV_{rms}. The lowest V_{min} value recorded was 63 kV during scenario 9, which is 40% higher than the insulator's normal operating voltage. This result suggests that composite insulators perform very well when subjected to volcanic ash contamination ranging from light to heavy pollution severity (Ave. ESDD/NSDD 0.04/15.2 – 0.6/218 mg/cm^2).

Trends in the composite long-rod results differed from other insulators'. Scenarios 6 and 7 for the composite specimen produced anomalous flashover data – where one or more tests showed significantly lower V_{min} values than anticipated. Inspection of the insulator following the inconsistent round in scenario 6 revealed that minor amounts (<20% surface coverage) of ash had accumulated on the underside of weathersheds (Figure 5.14). As these surfaces were free of contamination before the test, it was determined that ash had splattered onto the underside of weathersheds from the force produced by flashover arcs. From this observation it can be said that even small deposits (e.g. <20% surface coverage, <1 mm thick) of wet ash on the underside of composite insulator sheds can greatly reduce the insulator's pollution performance.

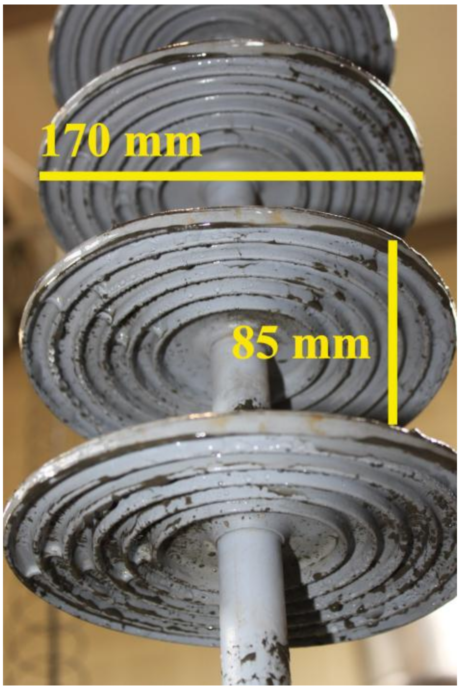

Figure 5.14: Underside of the composite insulator (shed diameter = 170 mm, shed spacing = 85 mm) following the completion of scenario 7, Round 1. This round of tests produced an anomalously low V_{min} value, which is likely the consequence of ash splattering onto the underside of weathersheds with each flashover, thereby reducing the protected creepage distance.

5.7.1.3 RTV coating

Pollution performance curves in Figure 5.15 suggest the RTV treated specimen slightly outperformed (had higher dielectric strength than) the unmodified glass insulator for most scenarios. However, a lack of available data for pollution severity classification of contamination with NSDD >4 mg/cm^2 in IEC 60815-1 (2008), and the knowledge that excessive deposits of pollution and/or excessive electrical stresses causing surface discharges can significantly reduce the performance of a RTV-coated insulator (IEEE 1523, 2002), support the possibility that high NSDD of the pseudo ash overwhelmed the coating's hydrophobicity. Hence, the minor improvement

(~10%) in pollution performance would not justify the benefit of using RTV coatings on HV insulators in ashy environments.

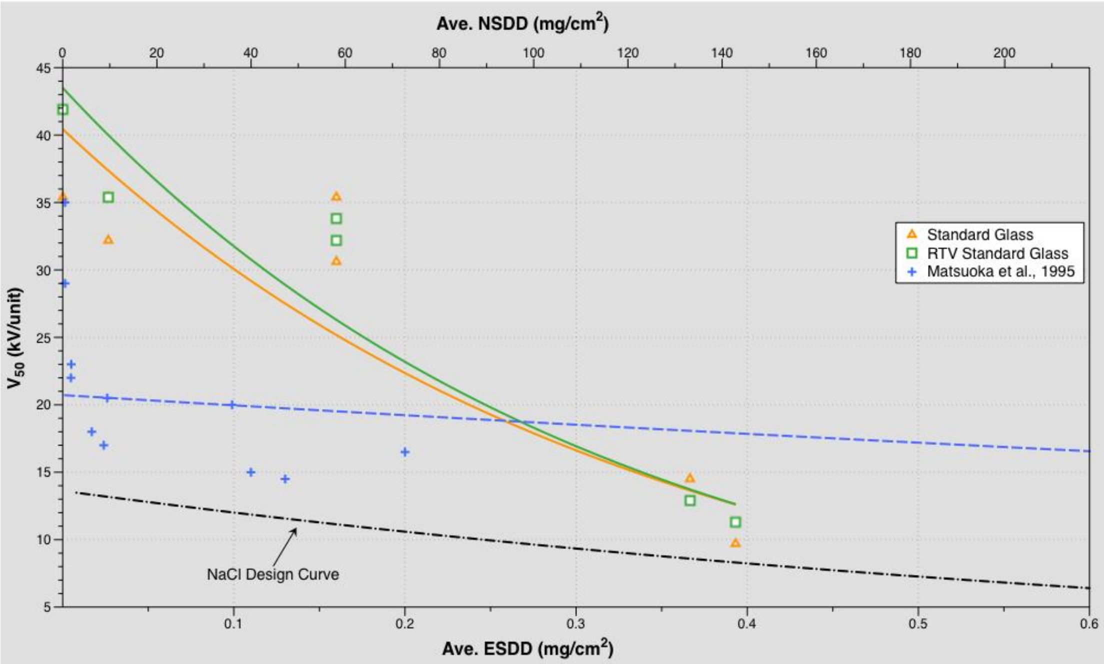

Figure 5.15: V_{50} curves for the standard glass and RTV treated insulators for scenarios 3-9. The NaCl design curve and volcanic ash data from Matsuoka et al. (1995) have been added for comparison.

5.7.2 Other considerations

For contaminated scenarios, results generally show an initial reduction in the flashover voltage and the V_{min} reached some time after. However, following a slight recovery of the dielectric strength as solubles were likely leached from the ash, flashover voltage values levelled off. This is probably due to the pooling/retaining of water within the ash deposit, as the simulated rain was not heavy enough to wash away the ash, even in light pollution scenarios (e.g. 4 and 5) (Figure 5.16). Rain water has an inherent conductivity. Thus, if ash is not washed naturally or anthropogenically from insulators, the ash will retain the moisture and, in turn, affect (1) the run-off rate of soluble material, (2) the hydrophobicity of the insulator surface, (3) the evaporation rate of the wetted layer, and (4) the local electric field strength (Farzaneh and Chisholm, 2009).

Figure 5.16: Residual ash on (from left to right): porcelain, standard glass, aeroform, composite, and RTV standard glass following light pollution (1 mm thick deposit on top surface only) testing rounds (scenario 4 or 5).

All insulators displayed equal or higher V_{50} values during scenario 2 than in scenario 1. This suggests that dry volcanic ash will not reduce the flashover voltage of HVAC suspension insulators. While dry volcanic ash presents a low probability of flashover occurring immediately after deposition, there is still a latent risk of flashover as subsequent atmospheric moisture (e.g. fog, dew, rain etc.) will wet the deposit and render it conductive (Chapters 2, 3, and 4). Thus, if the insulator’s protected creepage distance has been sufficiently reduced, immediate cleaning of insulators in critical sections or nodes of the power system, such as generation yards and substations should be considered.

The consistency of dielectric strength values across the range of insulators for these scenarios may be partially explained by limitations inherent in the artificial wetting process. Since the nozzle was configured perpendicular to insulator strings, the horizontal introduction of light rain meant little moisture could billow upwards and wet the underside of the specimen. Thus, high partial discharge activity and arcing, particularly on the underside of ceramic insulator sheds (closest to the pin), dried the ash layer significantly (Figure 5.17). The resulting high resistance of this dried ash layer effectively increases the protected creepage distance, which may have had a considerable influence on V_{50} values and thereby underestimated the vulnerability of the specimen insulators to ash contamination. Therefore, further laboratory tests should be carried out using a more robust artificial wetting system which can successfully wet the underside of weathersheds during test rounds.

Figure 5.17: Discharging and flashover across the **a)** standard glass and **b)** composite insulators, respectively. High heat generated from the plasma arcs dried ash deposits (lighter gray areas) on the underside of insulator sheds (**c and d**), effectively increasing the creepage distance and therefore the V_{50} values.

Chapter 3 showed that uncompacted deposits of coarse-grained ash (e.g. >1 mm particle diameter) often had a higher conductivity than those of fine-grained (e.g. <0.1 mm). This was attributed to the superior ability of coarse-grained ash to allow more rapid and extensive infiltration of moisture. Results from this study show that, while the V_{50} between the two pseudo ash size fractions differed slightly with each scenario, the coarse-grained ash most often produced the lowest V_{min} values. For the most heavily contaminated scenarios (8 and 9), the <1 mm pseudo ash caused the lowest V_{min} values for all insulators. Coarse-grained ash (e.g. >1 mm particle diameter) may therefore present a higher flashover risk in the immediate instance.

5.7.3 Surface degradation

Superficial damage to ceramic insulator sheds was observed following each round of tests in scenarios 8 and 9 (Figure 5.18). Inspection of shed surfaces after cleaning revealed etching and gouging of small channels typically 1 mm wide, 1-2 cm in length, and 1-2 mm deep, often embedded with ash particles. It appeared that ash particles partially melted and fused together to form a lustrous glass similar to obsidian, especially near the pin on the underside of weathersheds or the cap on the top. Considering the melting point of primary mineral constituents in a typical olivine basalt ranges from ~1,000 °C to 1,300 °C (Cox et al., 1979), and discharges during the flashover process can reach temperatures >3000 °C (Farzaneh and Chisholm, 2009), it is possible that arcing from partial discharging and repetitive flashovers, particularly in areas of high discharge activity, generated heat in excess of 1000 °C to melt and fuse ash particles to the insulators' surfaces. This has implications for operational performance, as small voids or imperfections can propagate under stress and ultimately decrease the insulator's electrical and mechanical strength (Rawat and Gorur, 2009).

Figure 5.18: Superficial damage to weathersheds from high discharging activity during the most heavily contaminated scenarios (8 and 9).

5.7.4 Limitations in experimental design

Due to some limitations in the UC test apparatus, implications arising from results in this study may be augmented by further testing. These should consider the following:

1. Test supply should have a short-circuit current rating >6 A as prescribed by IEC 60507 (1991) and IEEE Std 4 (1995);
2. An adequate artificial wetting process is required to wet both the top and underside of insulators so as to maintain high conductivity of the ash layer;
3. Insulators of different orientation and profile (e.g. high-creepage and hollow designs such as those intended for capacitors, surge arresters, circuit breaker chambers and supports, cable terminations, wall bushings, transformer bushings, instrument transformers and other measuring devices) should also be evaluated to better constrain their effect on the flashover voltage characteristics of HVAC insulators.

5.7.5 Ash hazard intensity measure

Chapter 4 outlined several limitations in the ESDD method as a rapid means of assessing the pollution severity of freshly falling/fallen ash. Similarly, using the ESDD/NSDD method to interpret ash pollution severities within the laboratory is problematic. Increasing accumulations on the top surfaces of a suspension insulator will increase the total (top and bottom surfaces) ESDD/NSDD values despite the underside being shielded from ashfall. ESDD values taken only from the top shed therefore do not accurately represent the total pollution severity. Thus, the use of an average of ESDD/NSDD on both top and bottom surfaces of the insulator is recommended over individual top and/or bottom measurements as this study shows heavy ESDD levels (up to 0.6 mg/cm^2) on just the top surfaces will not critically affect the pollution performance of a suspension insulator. Accordingly, there is need for a common measure of contamination severity during volcanic ashfalls. When considering the likelihood of flashovers occurring on HVAC suspension insulators following ashfall, we recommend the distribution and percentage coverage of the protected creepage distance is a more reliable and accurate hazard intensity parameter than other common metrics used, such as ashfall thickness or load.

5.9 CONCLUSIONS

Five different insulators were artificially contaminated with volcanic ash and put through a modified clean-fog rapid flashover testing programme. The following conclusions can be drawn from this study:

1. All insulators tested in this study performed comparably when subjected to critical contamination scenarios (i.e. top and bottom surface coated in ash). However, the standard glass insulator displayed the lowest V_{50} value of all specimens, 29 kV/m or 10 kV/unit (ESDD/NSDD = 0.4/152 mg/cm^2), which is comparable to those observed in the historic investigations of Nellis and Hendrix (1980) (11 kV/unit) and Matsuoka et al. (1995) (8 kV/unit);

2. Results from this study provide insulator performance curves to aid the appropriate selection of HVAC insulators for ashy environments. The composite polymer insulator exhibited the highest dielectric strength (V_{50}) for the majority of scenarios and is therefore likely to outperform ceramic equivalents in areas with a high ashfall hazard. However, anomalous V_{min} values for this specimen during scenarios 6 and 7 suggest that minor amounts of volcanic ash contamination (<20% surface coverage, <1 mm deposit thickness) can significantly reduce pollution performance;

3. With the exception of scenario 9 (6 mm top thickness, 1 mm bottom thickness, <1 mm particle size), the aeroform insulator consistently displayed the lowest dielectric strength of all specimens during contaminated scenarios. This is likely due to the balance (equivalence) of creepage distance on the top and underside of the insulator and implies that aeroform suspension insulators are more likely to flashover during ashfalls than other ceramic or non-ceramic equivalents. However, the superior self-cleaning properties of the aeroform profile suggest it may be more effective in the horizontal configuration (e.g. strain, dead-end, etc.);

4. Our results indicate that a suspension insulator which protects the underside of weathersheds from ashfall and/or moisture will effectively minimise the likelihood of insulator flashover. Thus, while not examined in this study, high creepage models such as fog or bowl profiles are expected to perform well during ashfalls and should be a focus in future contamination experiments;

5. Particle size has negligible influence on the V_{min} of HV insulators. As volcanic ash particle size tends to fine with distance from the source volcano, HV insulators are therefore vulnerable to flashover at both proximal and distal locations from the volcano;

6. Moderate accumulations of volcanic ash (e.g. 3 mm deposit thickness) on the top of insulator sheds will not critically affect the flashover voltage of HV insulators. This is significant as it suggests hazard intensity parameters currently used by volcanic scientists such as thickness should be revised to better reflect the variables most influential in reducing the flashover voltage of HV insulators. Results herein imply that percentage coverage of protected creepage distance is the primary control on the reduction of flashover voltage and should be included in field assessments of power system assets during future volcanic eruptions;

7. Results from this study provide insight into the performance of different insulator profiles and materials under varying degrees of volcanic ash contamination. Due to limitations in the UC testing apparatus, these tests should be repeated in other, more sophisticated laboratories to verify the effect of volcanic ash contamination on the flashover voltage of HV insulators and augment the data presented here.

5.10 ACKNOWLEDGEMENTS

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Chapter 6

Analysis of sinusoidal leakage current and partial discharge on HVAC suspension insulators artificially contaminated with volcanic ash

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OVERVIEW

Real-time, live-line diagnostic techniques are increasingly being used in power systems engineering to monitor the condition of apparatus. This chapter assesses the potential of sinusoidal leakage current magnitudes and partial discharge pulses in providing a practical means of monitoring the state of high voltage (HV) insulators during volcanic ashfalls. Early notification of critical conditions during ashfalls could help identify affected areas, accelerate system restoration, reduce outage time, and improve system reliability.

6.1 ABSTRACT

Pollution flashovers can result in expensive and lengthy power outages. A relatively rare but severe form of airborne pollution, volcanic ash contamination reduces the dielectric strength (pollution performance) of HV insulators. Analysis of sinusoidal leakage current (LC) is a common technique used to assess the condition of energised insulators under contaminated conditions. This chapter presents a summary of results and observations from 50 Hz LC measurements on five different HVAC (High Voltage, Alternating Current) insulators artificially contaminated with a volcanic ash proxy. An exploratory analysis of the partial discharge (PD) activity is also investigated to augment existing LC flashover prediction practises. Results suggest large current surges associated with partial arcing are initiated once critically contaminated scenarios arise (i.e. ash covers top and bottom of insulator weathersheds). Cumulative charge from PD increases with increasing voltage, varies with contamination severity (e.g. wet or dry ash), and gradually decreases with time. Considerable differences in the spread of data between different insulators suggest other factors such as material, profile and dimensioning will have an effect on LC and/or PD. Further insight into LC and PD values gained from constant voltage (e.g. withstand) tests will complement the data herein to inform the development of a flashover prediction method for system operators and hazard managers looking to mitigate volcanic ash-induced impacts.

6.2 INTRODUCTION

Outdoor HV insulators are designed to withstand a range of mechanical, electrical and environmental stresses during intended service life. Despite decades of intensive research of HV insulators for use in different settings, the application of outdoor insulators has typically been learned by experience. Proper insulator design and maintenance depends on knowledge of the contamination flashover mechanism, operating environment, relative performance of each insulator type, and available maintenance methods (IEEE Working Group, 1979).

One of the most common sources of power disruption is the failure (dielectric breakdown) of polluted insulators (Farzaneh and Chisholm, 2009). Volcanic ash is a rare but severe form of airborne pollution capable of causing flashover across station and line insulators (Chapter 2). Ash-induced insulator flashover is the most common impact to electric power systems during and after ashfalls (Chapter 2). Soluble surface salts formed during particle-gas/aerosol interaction within the volcanic plume are responsible for providing ionic content to an otherwise electrically inert material (Chapters 3 and 4). The non-soluble component of volcanic ash (Chapter 4) also provides a binding material for water adsorption, which in turn affects the hydrophobicity of the insulator surface, evaporation rate of the wetted layer, and the local electric field strength (Farzaneh and Chisholm, 2009). Large volumes of ash may be deposited over extensive areas (hundreds to thousands of square kilometres) and in a short space of time (e.g. up to ≥10 mm/hr) (Chapter 2). The high level of exposure of HV insulators to ashfalls and vulnerability to the ash flashover hazard thus makes it important to identify critical operating thresholds to avoid large-scale outages.

A number of methods are used to assess pollution levels (severity) on energised insulators, however, monitoring fundamental frequency LC has been the most intensely studied (Lambeth et al., 1972; CIGRE WG 33.04 1979; Looms, 1988). Three primary analyses can be performed on LC data (after CIGRE TF33.04.03, 1994):

1. Surge counting, where the number of current pulses above a fixed amplitude is measured for a given period of time while the insulator is energised to its normal service voltage. This method is based on the fact that LC surges usually precede the final phase of pollution flashover (i.e. both the frequency and magnitude of pulses increases as flashover is approached);
2. Determination of the highest peak current (I_h) recorded over a given period of time on an insulator continuously energised at its service voltage.

3. Charge measurements (*ΣQ*), where the LC is interpreted as a cumulative measure of charge over a set period of time.

Of these, evaluating the magnitudes and rms (root mean square) values of sinusoidal (50 or 60 Hz) LC ‘surges’ during partial arcing activity leading up to flashover is the most common (e.g. Sforzini and Schneider, 1979; Li et al., 2009; Ramirez et al., 2012). Significant effort has been placed in developing LC analysis to forecast insulator flashover, however, the predominantly random process of pollution flashover and the stochastic nature of LC magnitudes makes its prediction a complex task (Amarh et al., 2002; Li et al., 2009) and reliability questionable (Lloyd and Schneider, 1982; Farzaneh and Chisholm, 2009).

Related to LC monitoring, PD analysis is used to assess the condition and integrity of insulation on or within electrical apparatus. PD is defined as a localised electrical pulse, discharge or avalanche of charge that does not completely bridge the insulation between electrodes (IEC 60270, 2000). Each pulse consists of a voltage and current signal into the insulation, returning through a ground (earth) or other low impedance path. The number, magnitude and polarity of these PDs can be a direct indication of the condition of the insulation system. Accordingly, abnormal levels of PD may indicate (after Hardie, 2006):

1. Voids in the insulator;
2. De-lamination or deterioration of insulator surfaces;
3. Cracks or fissures in broken insulators;
4. Electrical treeing (a damaging process due to partial discharges progressing through the insulation, in a path resembling the branches of a tree (Olyphant, 1963)) in and/or on the surface of the insulator;
5. Abnormal electrical stress areas due to improper manufacture or application.

This form of dielectric monitoring is an effective technique for signalling imminent failure in power system apparatus (Ward and Lindgren,

2000) such as transformers (e.g. Bengtsson, 1996), cables (e.g. Smit et al., 2002), motors (e.g. IEEE P1434 (2010)) and other system elements (e.g. switches, circuit breakers, capacitors, measuring transformers, generators, etc.).

Previous LC studies have typically been on insulators contaminated by other types of airborne contaminants (e.g. those detailed in Chapter 1) and energised with a constant voltage (i.e. measurements were taken either from in-service insulators operating at normal system voltages or during withstand tests within a laboratory) (e.g. Li et al., 2009; Ramirez et al., 2012). To augment the work in Chapter 5, this study focuses on LC and PD dynamics on contaminated insulators that were energised to successive voltage 'steps' leading up to flashover. Five different HV insulators (three ceramic, one composite polymer, and one RTV coated specimen) were chosen for analysis during a clean-fog rapid flashover testing programme (Lambeth, 1988). Insulators were artificially contaminated with a pseudo ash (Chapter 3) on the top or both top and bottom surfaces of weathersheds (i.e. the insulating surfaces). The aim was to see how increased levels of contamination severity and different ash parameters (e.g. electrical properties influencing ash conductivity such as particle size) would affect I_h and/or PD magnitudes. Based on these preliminary findings, the potential for real-time monitoring of sinusoidal LC activity and PD pulses on HV insulators during volcanic ashfalls is considered.

6.3 EXPERIMENTAL SET UP AND PROCEDURES

Three primary factors control the contamination discharge and amount of current flow across the surface of an insulator: (1) operating voltage, (2) contamination severity, and (3) weather conditions (Kumosa et al., 2005; Li et al., 2009). To perform a comprehensive analysis of the influence that these and other factors have on LC and PD, several electrical tests were carried out in the University of Canterbury HV laboratory on artificially polluted suspension insulators to represent volcanic ash contamination in either a dry or wet environment. Ohm's law states that, for an electrical circuit with a constant resistance, the flow of current is proportional to voltage. Thus, while the surface resistance of the insulator (with possible contamination) may vary with multiple factors such as moisture content and time, it is expected that increasing the applied voltage in steps during flashover tests will typically correspond with higher cumulative LC and PD values.

The voltage source, insulator specimens and artificial wetting process used for the 9 different contamination scenarios are those described in Chapter 5. In summary, three rounds containing 15 or more rapid-flashover tests were conducted for each of the 9 contamination scenarios (Table 6.1).

Table 6.1: The 9 different contamination scenarios used in this study (from Chapter 5).

Scenario	Replicated environment	Wetting rate (mm/hr)	Ash top (mm)	Ash bottom (mm)	Particle size (mm)
1	Clean insulator in a dry environment	0	0	0	N/A
2	Light contamination in a dry environment	0	1	0	<0.1 or <1
3	Clean insulator in a wet environment	6	0	0	N/A
4	Light contamination in a wet environment	6	1	0	<0.1
5	Light contamination in a wet environment	6	1	0	<1
6	Moderate contamination in a wet environment	6	3	0	<0.1
7	Moderate contamination in a wet environment	6	3	0	<1
8	Heavy contamination in a wet environment	6	6	1	<0.1
9	Heavy contamination in a wet environment.	6	6	1	<1

Within each test, a specified voltage was applied across the insulator in a series of levels (steps). Each voltage step was maintained across the insulator for 2 minutes until a withstand or flashover resulted. While testing at each voltage level, a series of ten raw waveforms or 'epochs' were collected by an oscilloscope, each epoch containing 10 power cycles (or 0.2 seconds at 50 Hz) of fundamental frequency data sampled at 5 MSa/sec (down-sampled from a 'peak detect' sample rate of 2 GSa/sec).

Raw sinusoidal LC flowing through the earth path and PD pulses were measured using a shunt resistor (IEEE Std 4, 1995), with the oscilloscope connected to the shunt via a 10:1 HV probe (Figure 6.1). A calibrated sphere gap was used to protect measurement apparatus from any excessive voltage surges during flashovers. A personal computer was used to collect the data from each epoch.

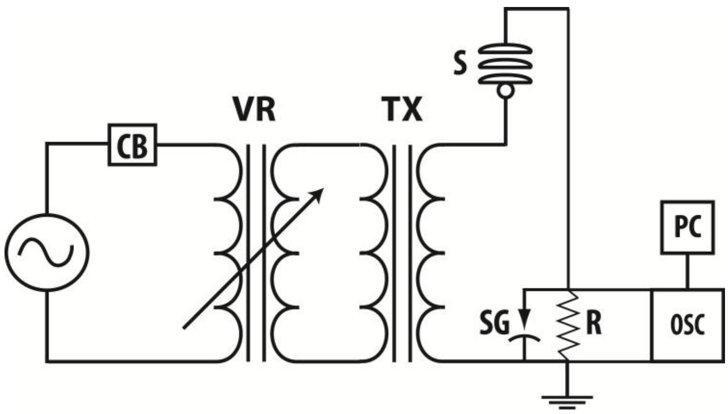

Figure 6.1: Test circuit. CB is the circuit breaker (600 A), VR is the voltage regulator, TX is the test transformer, S is the insulator specimen, SG is the spark gap, R is the shunt resistor (R=0.2 Ω), OSC is the oscilloscope and PC is the personal computer used for data collection.

6.3.1 Data processing

Data processing was carried out using Matlab, a PC software package that provides an environment for numerical processing. Matlab also provided features for communicating with external instruments and thus controlled the oscilloscope during epoch collection.

The raw waveforms from the shunt resistor and a reference 50 Hz voltage waveform were collected and filtered using analog filters to remove narrowband sources above the anti-aliasing frequency. The magnitudes of the PD pulses, measured in pico-Coulombs (pC), were calibrated using a pulse charge calibrator when the circuit was de-energised.

LC processing involved a Fourier Transform for determination of the 50 Hz magnitude. For PD pulse processing, the shunt resistor raw waveforms had DC (Direct Current) and 50 Hz (and harmonics) components removed using a digital filter. Pulses were then counted using a voltage threshold. Processed LC and PD results were discarded from epochs that were determined to contain flashover or other erratic signals.

6.4 RESULTS AND DISCUSSION

6.4.1 50 Hz leakage current

Figures 6.2-6.6 show LC recorded for 3 of the 5 insulators (aeroform, 66 kV composite long-rod, and RTV coated glass) across the range of scenarios (1, 2, 3, 8, and 9), plotted against test number (time). A negligible difference in LC between scenarios 1 and 2 was observed for all insulators, suggesting that dry volcanic ash does not initiate abnormal LC activity before flashover. This also supports other research (e.g. Nellis and Hendrix, 1980; Matsuoka et al., 1995; Chapter 3) which proposes dry volcanic ash is non-conducting, and therefore does not pose an immediate flashover hazard.

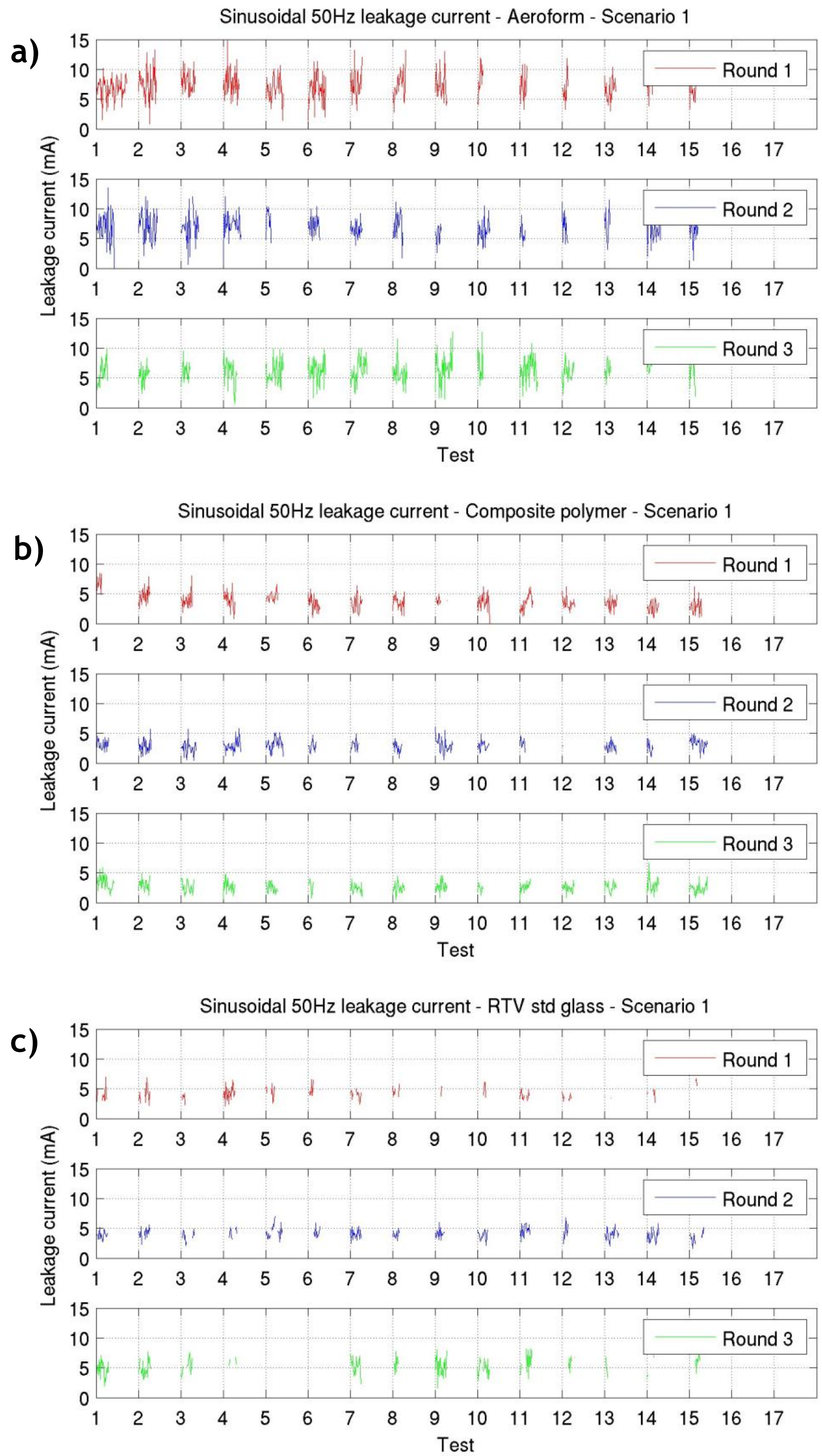

Figure 6.2: LC plotted against test number (time) for scenario 1 for the **a)** aeroform, **b)** 66 kV composite long-rod, and **c)** RTV coated insulators.

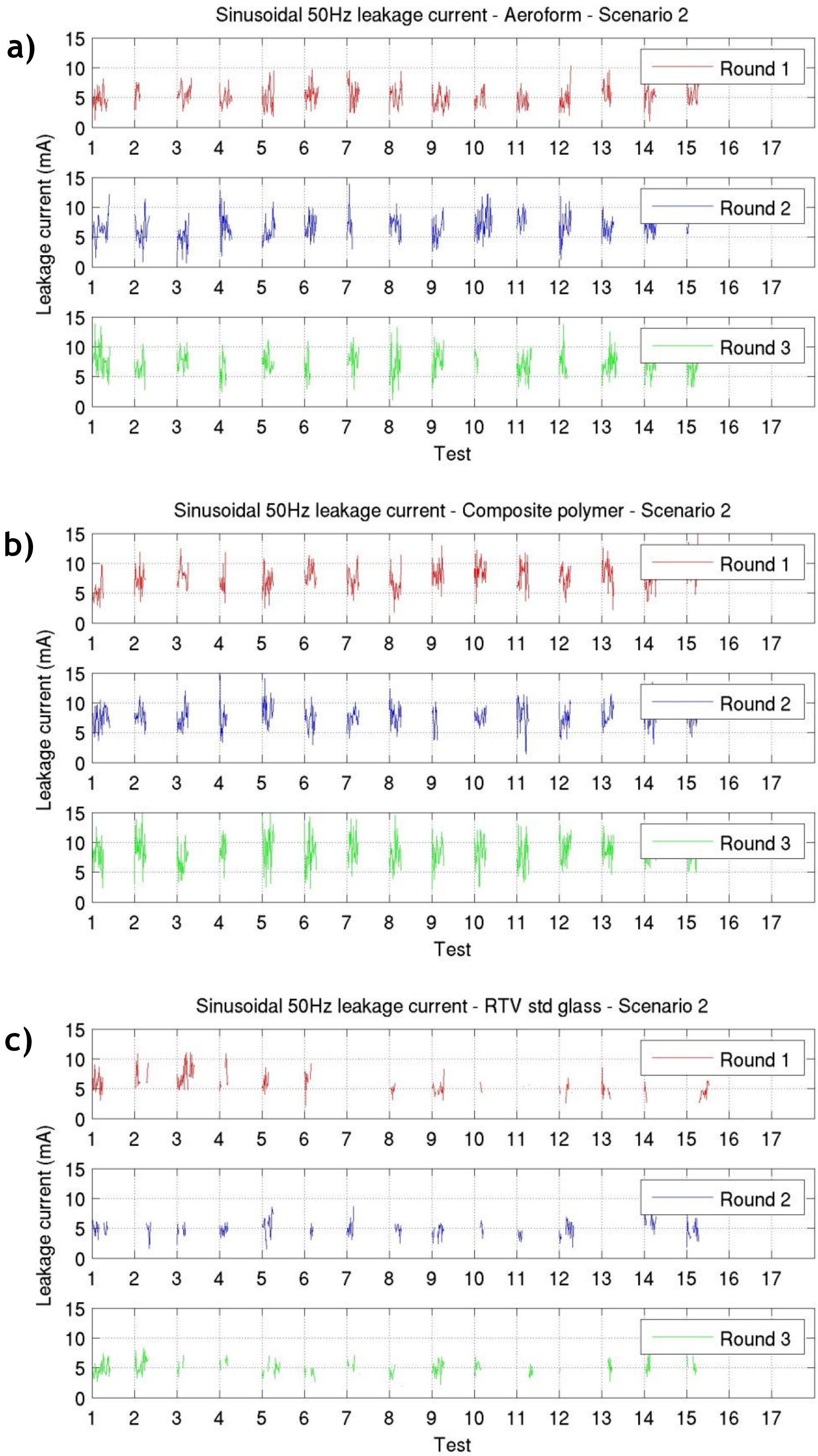

Figure 6.3: LC plotted against test number (time) for scenario 2 for the **a)** aeroform, **b)** 66 kV composite long-rod, and **c)** RTV coated insulators.

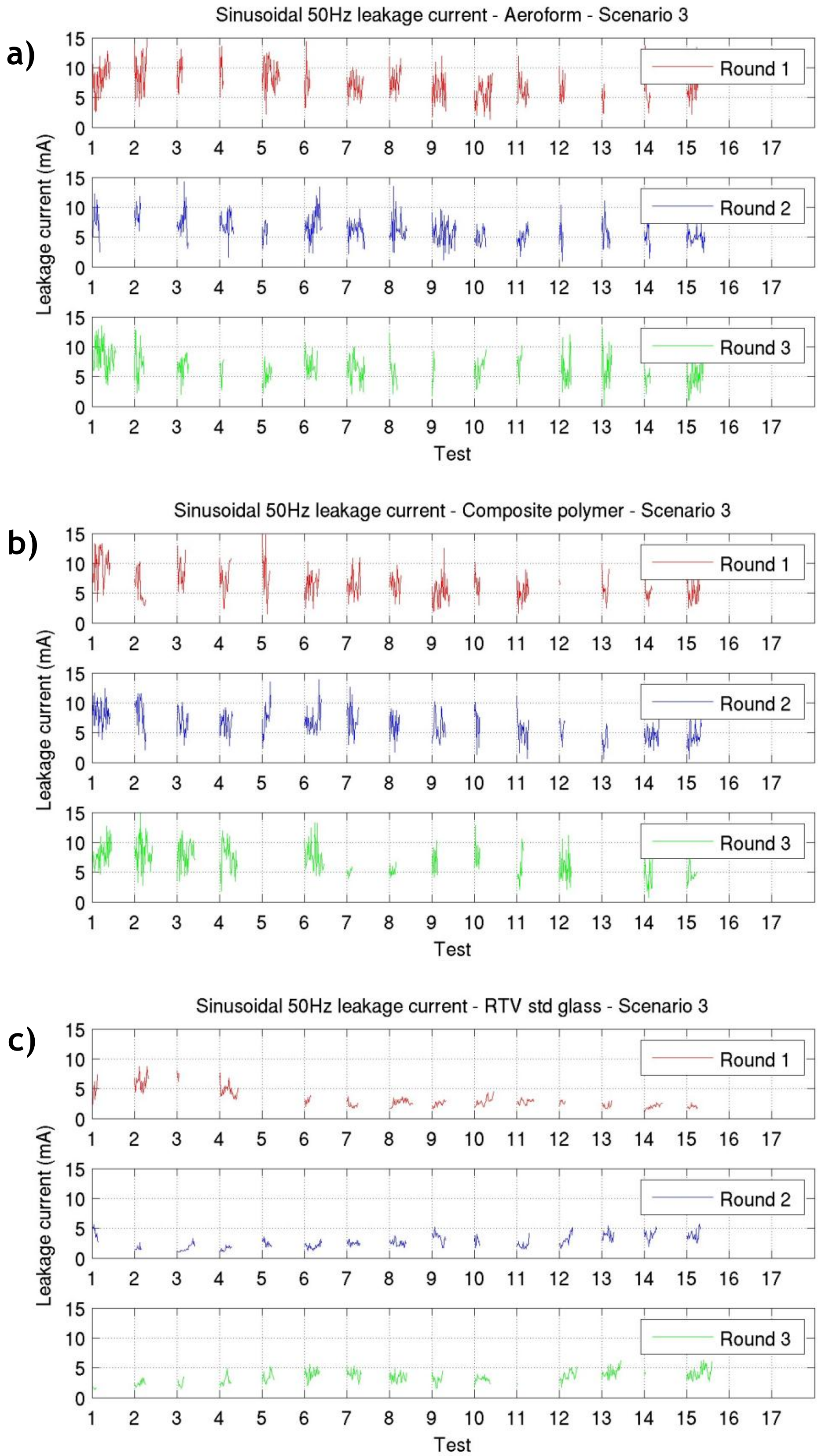

Figure 6.4: LC plotted against test number (time) for scenario 3 for the **a)** aeroform, **b)** 66 kV composite long-rod, and **c)** RTV coated insulators.

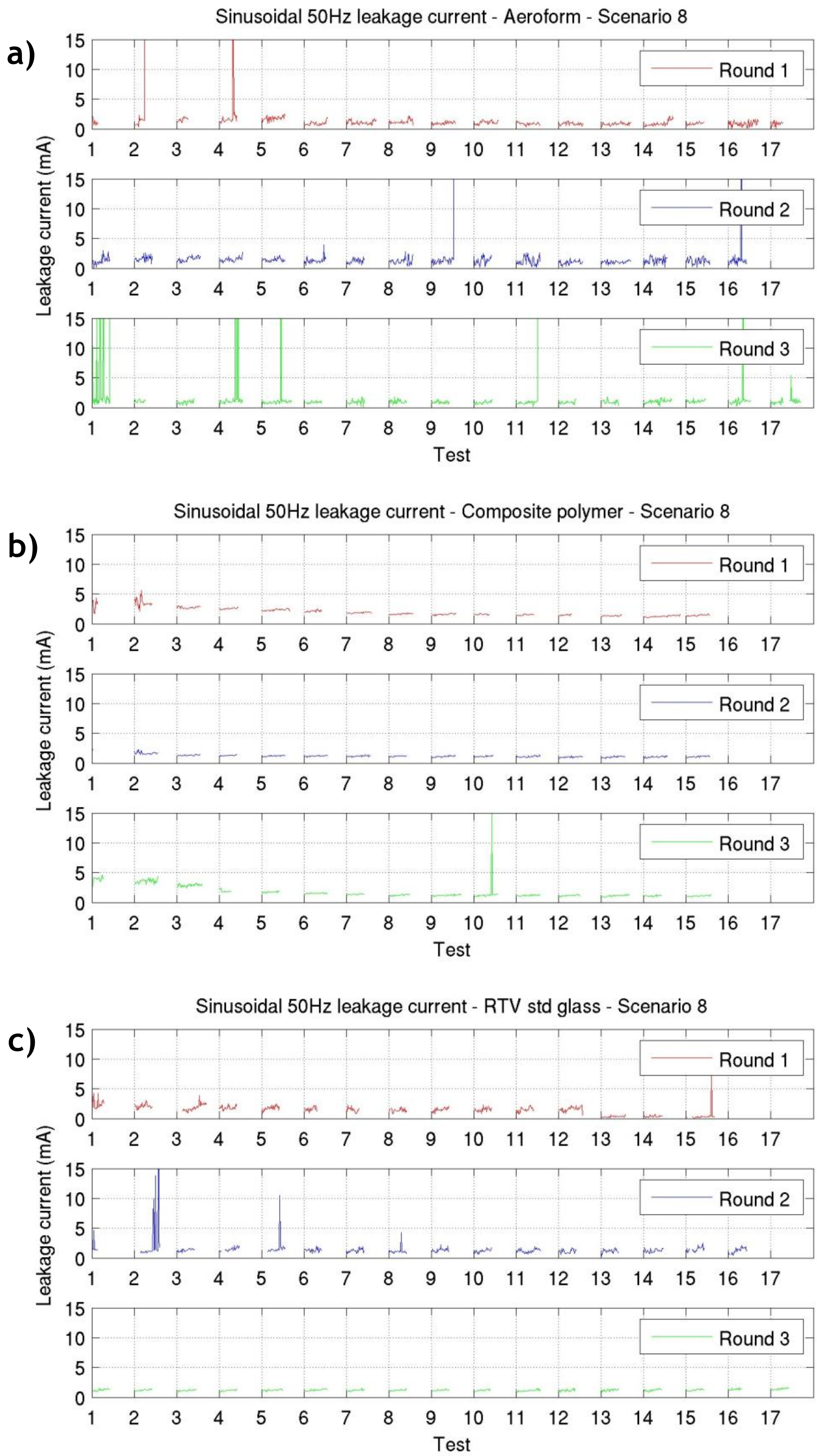

Figure 6.5: LC plotted against test number (time) for scenario 8 for the **a)** aeroform, **b)** 66 kV composite long-rod, and **c)** RTV coated insulators.

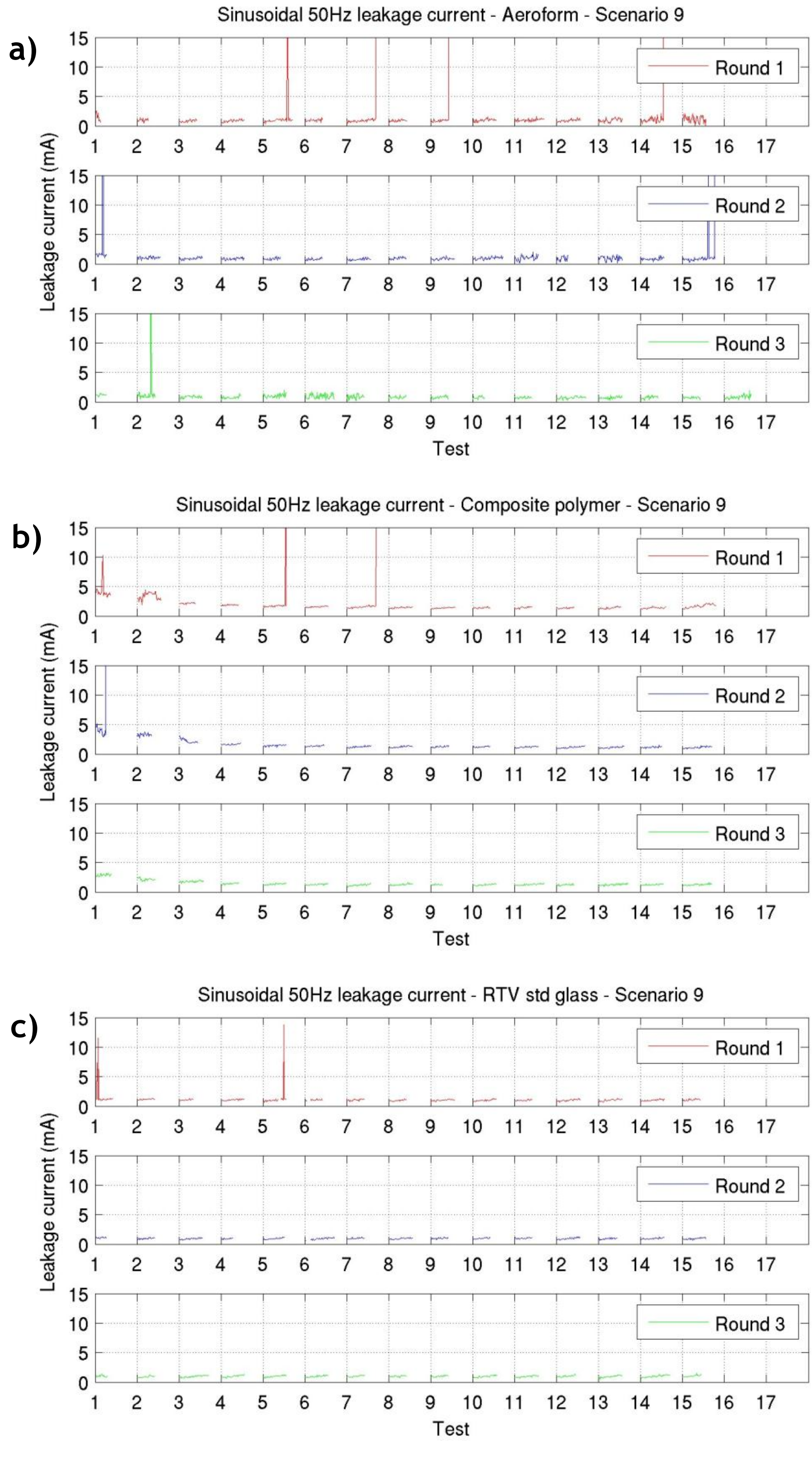

Figure 6.6: LC plotted against test number (time) for scenario 9 for the **a)** aeroform, **b)** 66 kV composite long-rod, and **c)** RTV coated insulators.

The average LC was lowest during scenarios 8 and 9 (i.e. when both top and bottom surfaces of the insulator were coated in ash). Current-voltage proportionality means this is primarily due to the lower applied voltage. Despite relatively low average LC values, however, Figures 6.5 and 6.6 show the I_h value of LC surges which were due to partial arcing activity and high scintillation. As there were several seconds of inactivity in between epoch data collection, much of the partial arcing/arc discharges and associated current surges could not be captured. Nevertheless, the highest recorded current surge was 136 mA during scenario 8 for the aeroform insulator. This value is slightly lower than those typically observed for clean-fog tests, where studies on other forms of pollution have observed peak LCs of up to 200 mA (Farzaneh and Chisholm, 2009). Thus, the high LC values in scenarios 8 and 9 (>50 mA) together with the absence of large current surges in scenarios 1-7 (Table 6.2) suggest that partial arcing and coinciding current surges will play a primary role in initiating ash-induced insulator flashover. Monitoring should therefore concentrate on the magnitude of these LC surges, as this and other studies (e.g. Farzaneh and Chisholm, 2009 and references within) suggest they are an indication of imminent flashover.

Table 6.2: Highest I_h values observed for each insulator and the corresponding scenario and round during which I_h occurred.

Insulator	I_h (mA)	Scenario	Round
Std Porcelain	119	9	1
Std Glass	26	8	2
Aeroform	136	8	1
66 kV Composite	114	9	2
RTV Glass	30	8	2

Dry scenarios (1 and 2) presented in Figures 6.2 and 6.3 showed little variation in LC throughout any one round, while wet contaminated scenarios often reached a maximum LC at some time during the testing round, and gradually decreased to a minimum. This trend may reflect the leaching process; where the ash layer absorbed moisture until a point of saturation (i.e. maximum layer conductivity), and the corresponding LC was highest and flashover voltage lowest. It is likely that, as the soluble (ionic) content was washed away from the ash, the resistance of the ash layer increased and the LC decreased accordingly. Thus, increasing LC at constant voltage will indicate a decrease in the ash layer's resistance and an increase in the likelihood of flashover (refer to Chapter 3 for more information on ash parameters affecting resistance). Similarly, the forces created by each flashover or partial arc often blew or removed some ash from the insulator surface (e.g. 5-10% of the total deposit). Removing part of the ash will create a higher resistance between conductive portions of the ash layer, which could cause a decrease in LC and/or PD activity.

Figures 6.7-6.11 summarise the LC for each insulator across all scenarios. As observed in other studies (e.g. Suda, 2005; Douar et al., 2010), the LC magnitude increased with increasing applied voltage. In general, increasing contamination severity (i.e. each successive scenario number) lowered the flashover voltage of the insulator (Chapter 5), which, due to current-voltage proportionality, corresponded with a decrease in average LC. In contrast, the average LC on the aeroform insulator decreased from scenario 4 to 7 at a constant applied voltage of 90 kV, suggesting that increasing volcanic ash contamination severity (ESDD/NSDD) may decrease the LC. This conflicts with Montoya-Tena et al. (2005), who found that LC increases with increasing ESDD/NSDD, albeit the NSDD levels were comparatively low (≤4.4 mg/cm^2 in Montoya-Tena et al. (2005) versus >30 mg/cm^2 for a 1 mm layer of volcanic ash in Chapter 4). Additionally, while scenario 4 contained the lowest flashover voltage for scenarios 4-7 (Chapter 5), it also showed the highest LC. These anomalous results suggest that other parameters will have an influence on LC such as insulator profile, insulator conditioning (IEC Std 60507, 1991), form factor and/or ash layer conductivity (not explored here) (IEC 60815-1, 2008), and that volcanic ash may induce different LC characteristics and/or behaviour than that observed with other pollution.

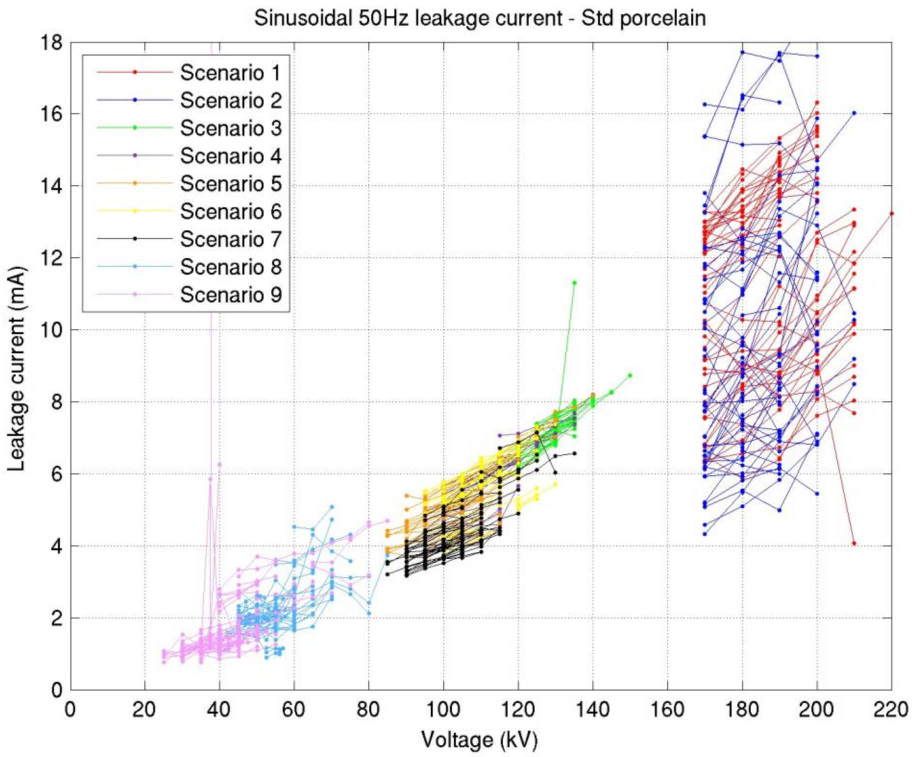

Figure 6.7: LC against applied voltage for the standard porcelain insulator.

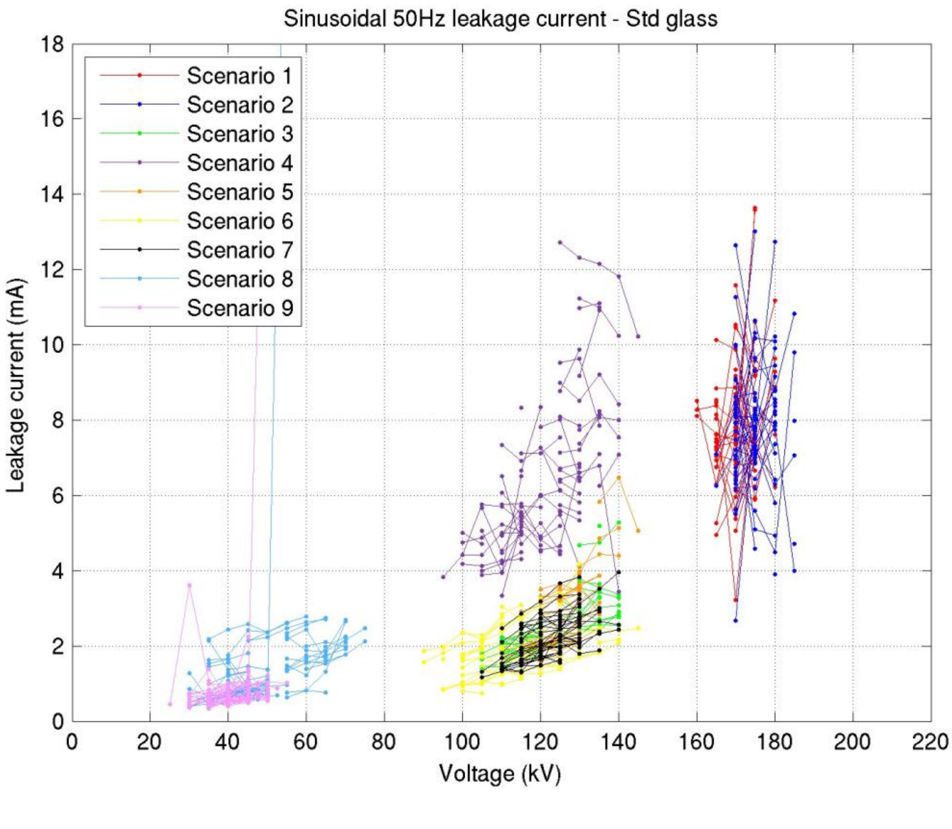

Figure 6.8: LC against applied voltage for the standard glass insulator.

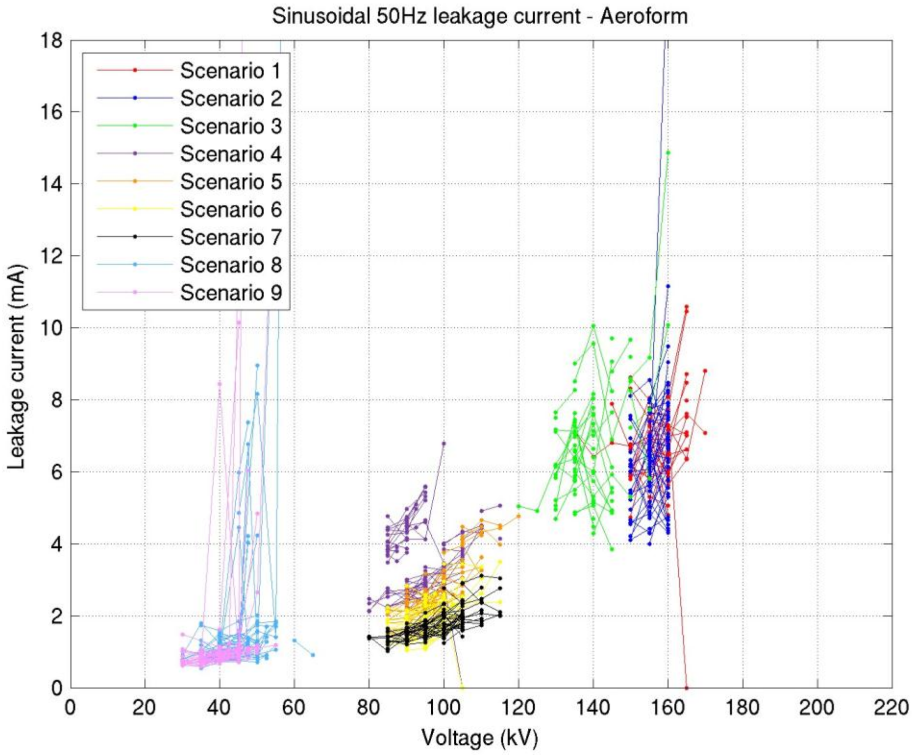

Figure 6.9: LC against applied voltage for the aeroform insulator.

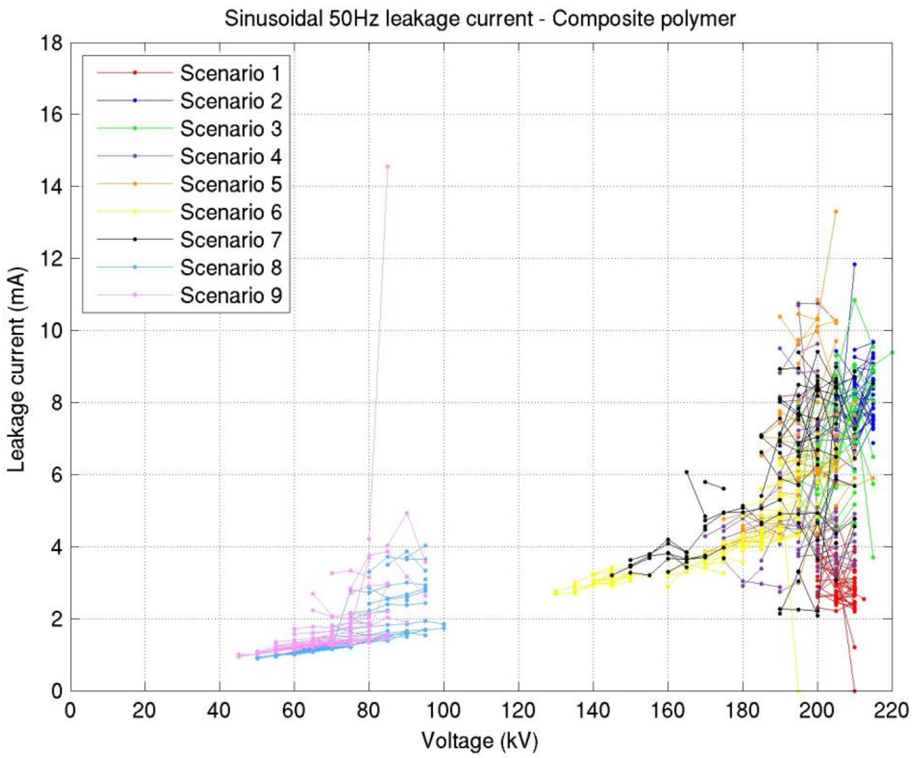

Figure 6.10: LC against applied voltage for the 66 kV composite insulator.

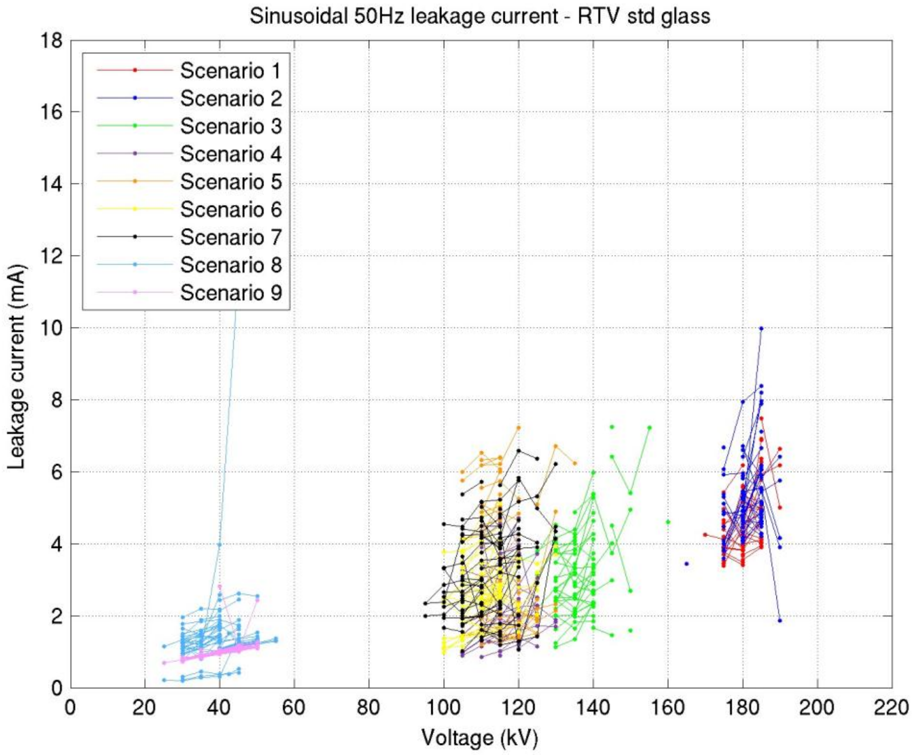

Figure 6.11: LC against applied voltage for the RTV coated insulator.

Excluding current surges, the standard porcelain insulator consistently displayed the highest average LC across all scenarios and had a particularly varied LC level during scenarios 1 and 2. While some of the LC variation in scenarios 1 and 2 are due to oscilloscope quantisation noise, results from Chapter 5 showed that this insulator had a higher pollution performance than most. The increased LC for the standard porcelain insulator therefore suggests that other factors such as material, profile, dimensions, etc. may contribute to the amount of LC, irrespective of contamination severity.

6.4.2 Partial discharge

As with LC, PD activity most often decreased with time (epoch) (Figures 6.12-6.14). This can be explained by changes in the ash layer's properties (e.g. moisture content, distribution of ash with successive flashovers, etc.) throughout the testing round, where changing ash layer properties will dictate the points of discharge.

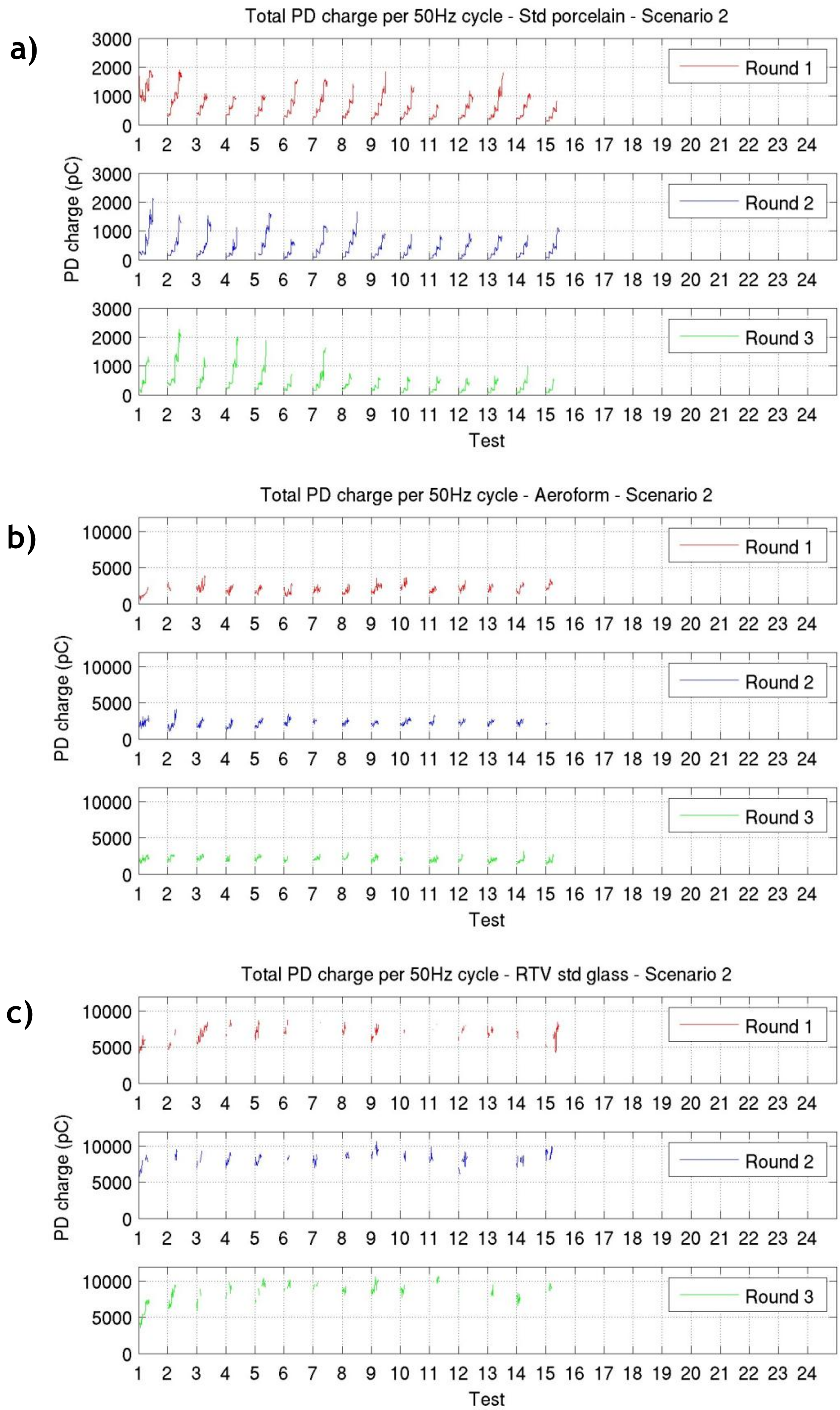

Figure 6.12: PD plotted against test number (time) for scenario 2 for the **a)** standard porcelain, **b)** aeroform, and **c)** RTV coated insulators.

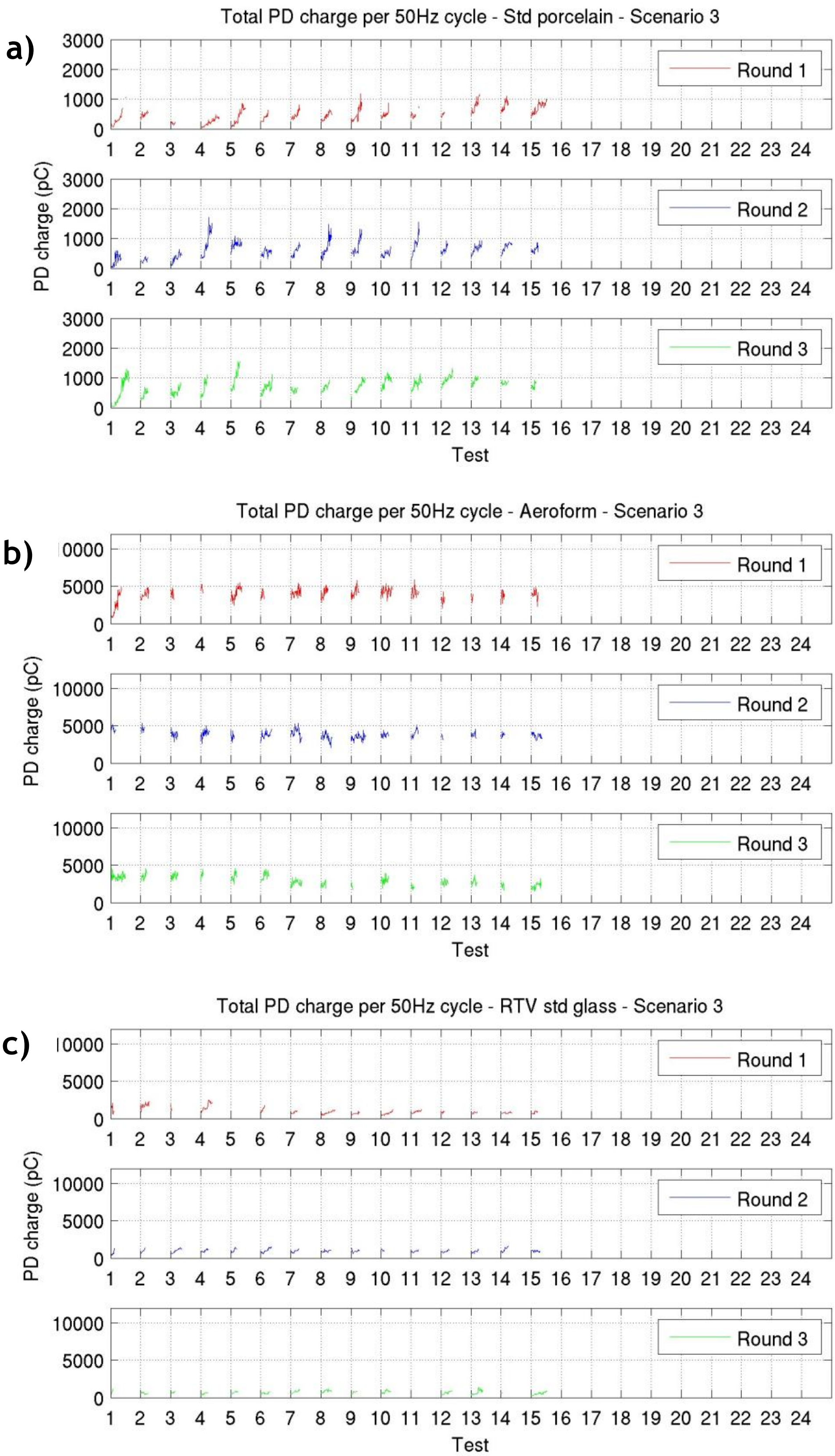

Figure 6.13: PD plotted against test number (time) for scenario 3 for the **a)** standard porcelain, **b)** aeroform, and **c)** RTV coated insulators.

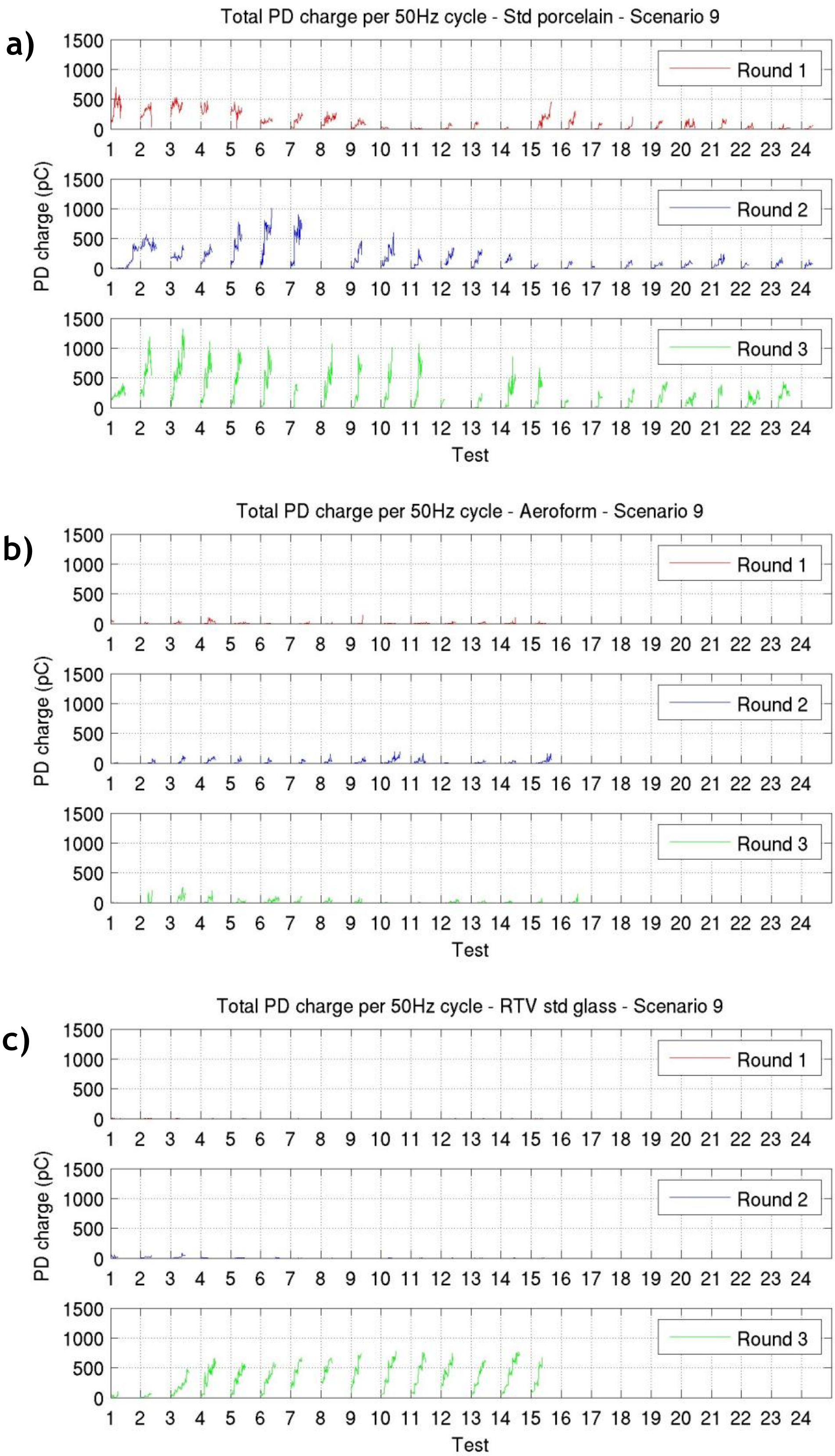

Figure 6.14: PD plotted against test number (time) for scenario 9 for the **a)** standard porcelain, **b)** aeroform, and **c)** RTV coated insulators.

PD pulses (i.e. the amount of charge) consistently rose with increasing applied voltage as a result of current-voltage proportionality. Individual points on each line in Figures 6.15-6.19 represent the cumulative charge that resulted at each applied voltage (step) within a specific contamination scenario (with the final point on each line indicating PD activity just before flashover). As the test voltages were within ~15% of flashover, the range or spread of each 'cluster' of PD values specific to each contamination scenario can therefore be interpreted as typical PD levels prior to flashover and the lowest final point values may be considered a critical operating threshold. However, these ranges varied considerably between different insulators. For example, increased levels of audible noise and visible corona discharge were noticed when testing the standard glass insulator. This corresponds with an increased level of PD pulsing over other specimens, suggesting that insulator properties (e.g. material and design) will affect the amount of PD. Thus, in order to holistically quantify the risk of flashover using PD monitoring, critical PD levels specific to each insulator type are required, and should be a major focus of future work.

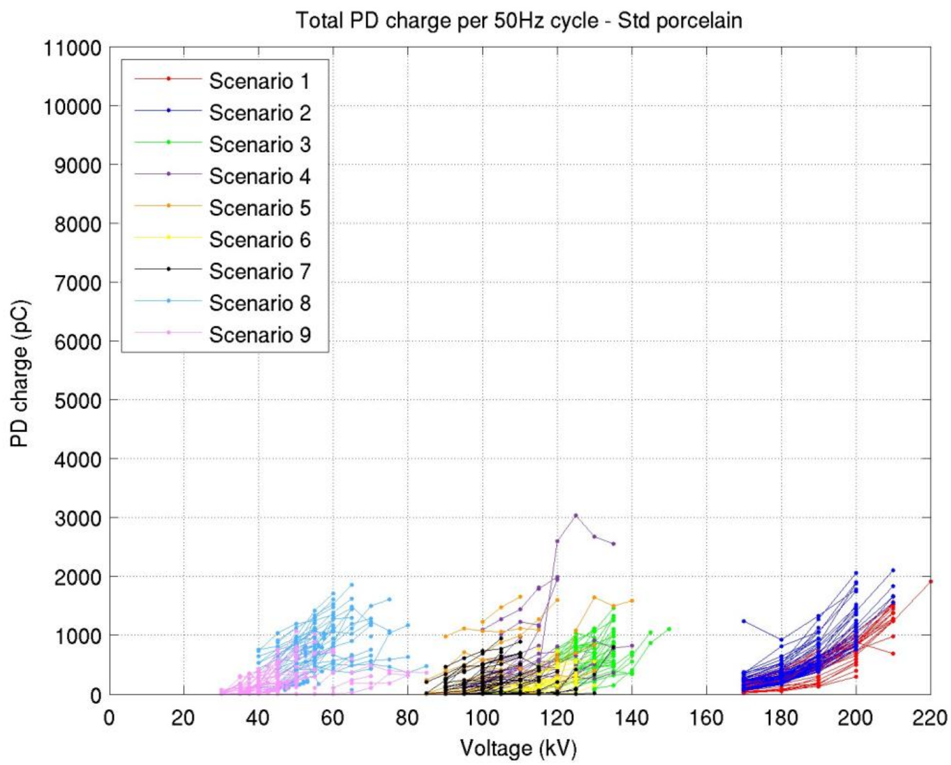

Figure 6.15: PD against applied voltage for the standard porcelain insulator.

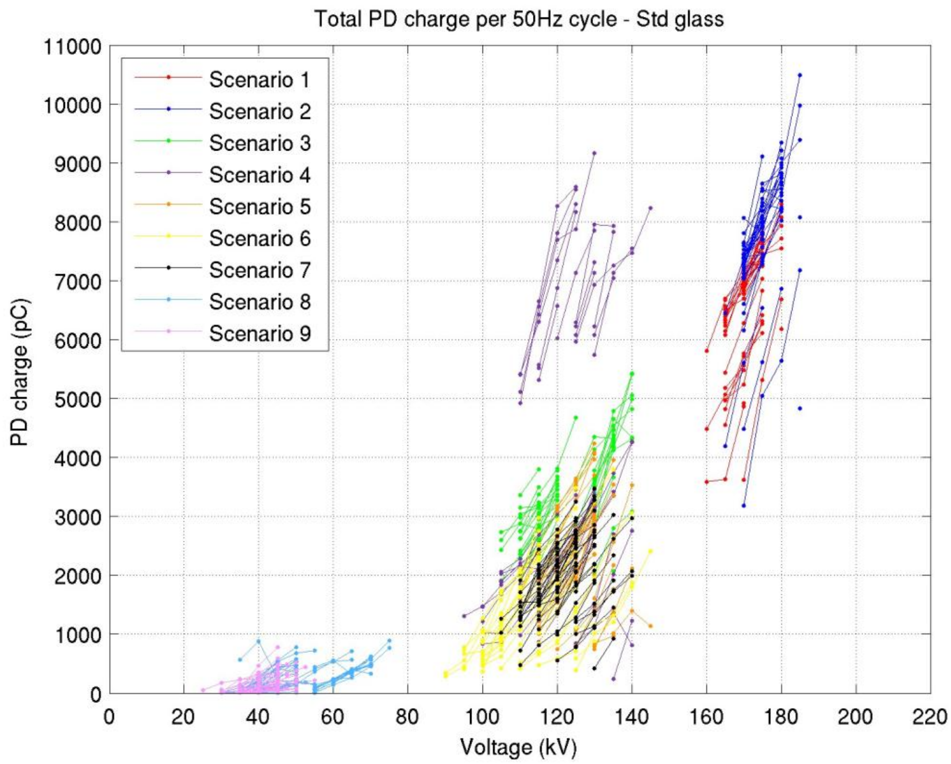

Figure 6.16: PD against applied voltage for the standard glass insulator.

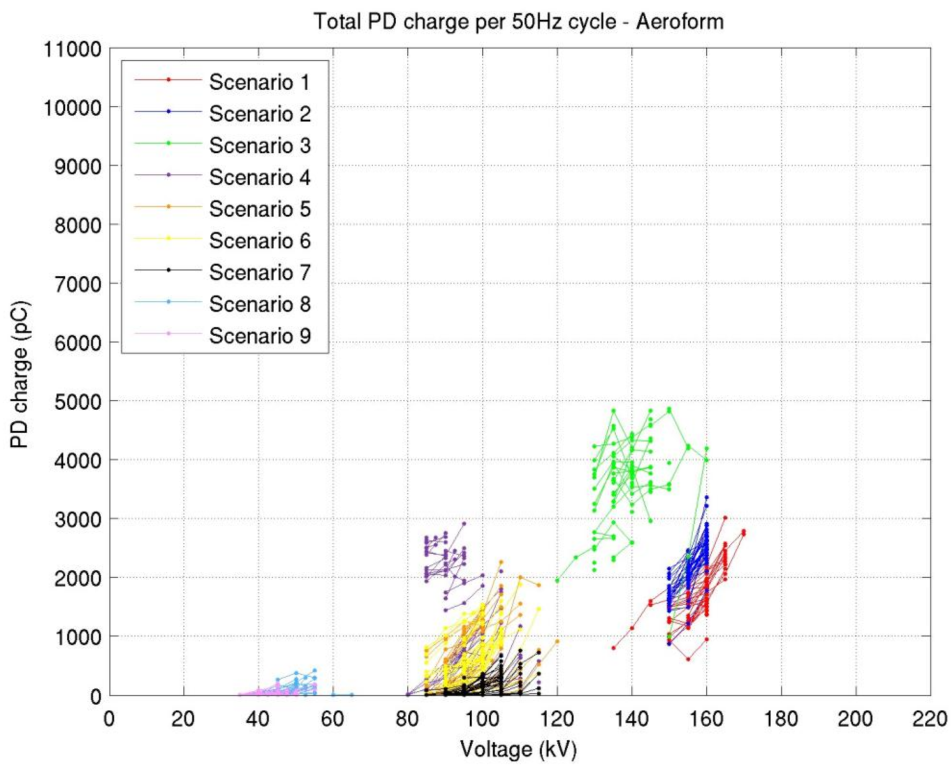

Figure 6.17: PD against applied voltage for the aeroform insulator.

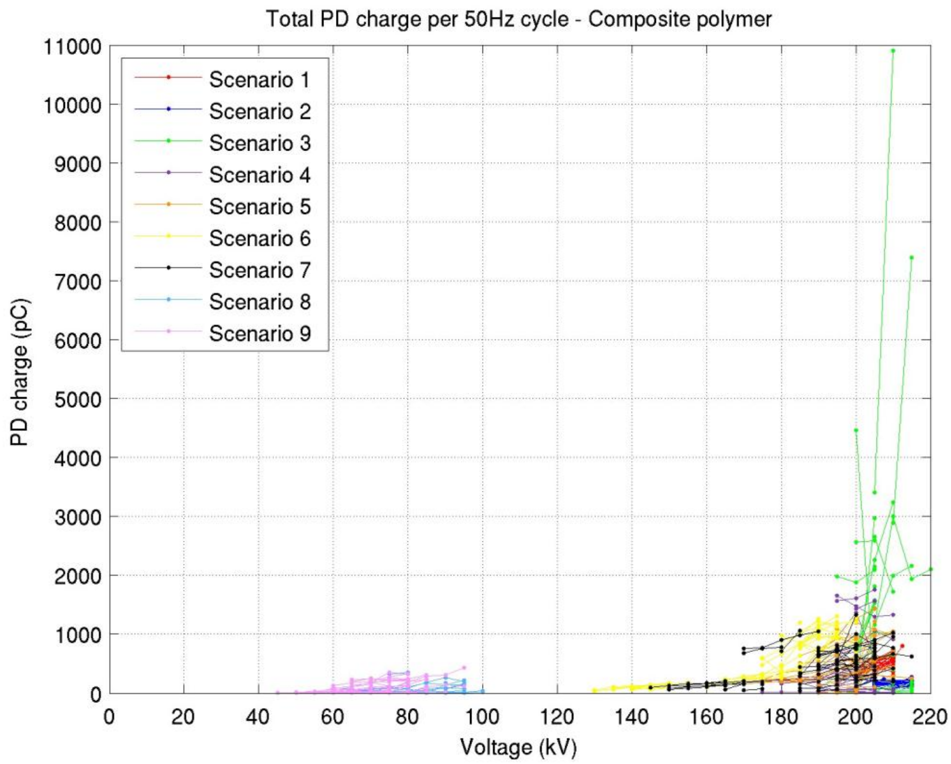

Figure 6.18: PD against applied voltage for the 66 kV composite insulator.

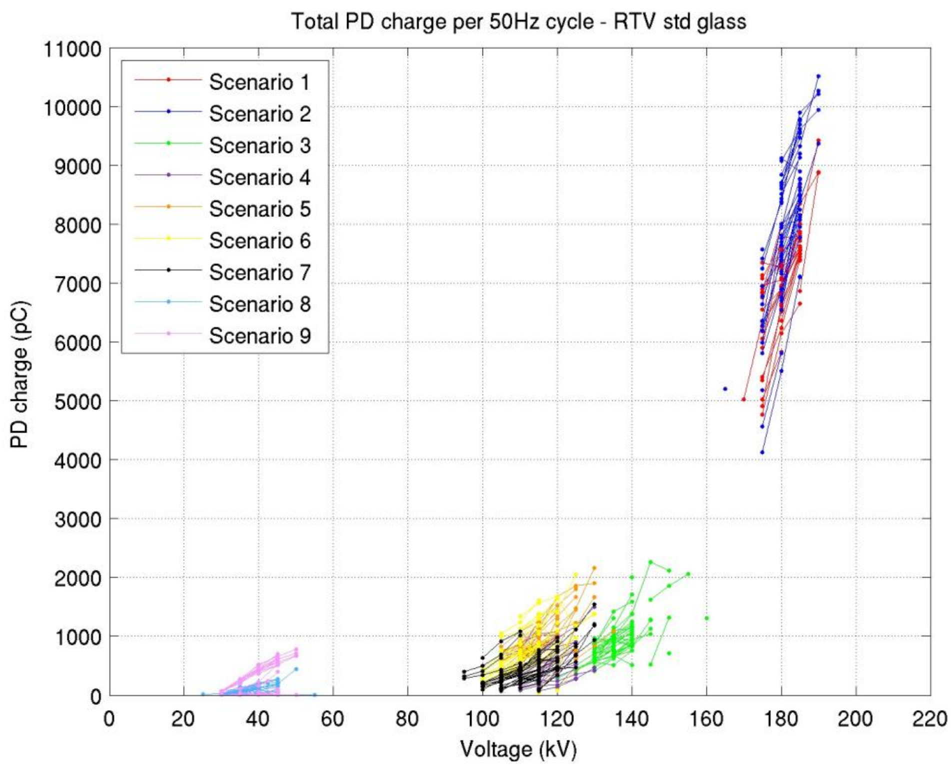

Figure 6.19: PD against applied voltage for the RTV coated insulator.

Results show that the RTV coating significantly suppressed PD activity (similarly to suppressed LC) compared to the untreated standard glass specimen (Figures 6.16 and 6.19). Similarly, the 66 kV composite polymer insulator generally showed lower PD activity than the ceramic equivalents. This may reflect the ability of silicone polymer materials to minimise LC and PD activity (IEEE Std 1523, 2002) and thereby potentially increase the flashover voltage and overall performance of an insulator during ashfalls. The data suggests that LC and PD will be lower on polymeric insulators than ceramic insulators of similar rating. Despite lower LC and PD levels for the RTV coating, however, flashover voltages were comparable. This suggests that other physical, chemical, environmental and/or electrical factors may have more influence on LC and PD than previously thought.

6.4.3 Predictive capacity of partial discharge analysis

Since the applied voltage was constantly changing, it is difficult to compare the results herein to those collected from in-service conditions (i.e. where the voltage is constant). However, analogous to current LC monitoring practises, future studies should focus on variations in pulse count, amplitude and/or timing with reference to fundamental frequency phase angle, and may provide an indication of impending flashover. As already established, an increase in pulse amplitude is observed with increasing applied voltage. Pulse pattern variation requires further analysis, but it is believed that the PD monitoring method has potential for live-line application during ashfalls.

6.5 CONCLUSIONS

The problem of insulator contamination and subsequent flashover does not have a unique and simple solution. Live-line diagnostic techniques used to monitor the operational state of an insulator during volcanic ashfalls have potential to predict ash-induced insulator flashover. This study presents the results from an exploratory analysis of LC and PD on 5 different insulators subjected to varying ash contamination severities. The data suggest the following preliminary conclusions:

1. Dry scenarios (1 and 2) showed little variation in LC throughout any one round, while wet contaminated scenarios often reached maximum LC (lowest resistance) at some time during the testing round, and gradually decreased to a minimum (likely due to the leaching of soluble material, and associated increase in ash layer resistance). Increasing LC over time at constant (or normal operating) voltage will therefore indicate a decrease in the ash layer's resistance (due to increasing moisture absorption) and an increase in the likelihood of flashover;

2. A negligible difference in LC between scenarios 1 and 2 was observed for all insulators, suggesting that dry volcanic ash does not initiate abnormal LC activity before flashover. This is in agreement with other research which suggest dry volcanic ash is non-conducting, and therefore does not pose an immediate flashover hazard;

3. Average LC was lowest when both top and bottom surfaces of the insulator were coated in ash, primarily because the applied voltage was lowest during these scenarios. Taking into account current-voltage proportionality, increasing contamination does not appear to significantly increase LC. Anomalous results for the aeroform insulator here suggest LC slightly decreases with increasing contamination severity, however, more research is needed to understand the relationship between increasing NSDD and LC;

4. High LC surges (>100 mA) due to partial arcing activity and heavy scintillation were only observed during critically contaminated scenarios (i.e. top and bottom surfaces coated in ash). The highest I_h value recorded was 136 mA during scenario 8 for the aeroform insulator, which is slightly lower than those typically observed for other forms of pollution, where peak LCs of up to 200 mA are possible. Thus, partial arcing and coinciding current surges are one key indicator of the initiation of ash-induced insulator flashover.

5. The PD analysis used in this study is a novel approach to monitoring the condition of energised HV insulators subjected to volcanic ash contamination. The data and methodology herein will complement contemporary LC practises;

6. PD pulses (i.e. the total amount of charge) increase with increasing applied voltage. The range of PD values in each cluster of scenario data represent preliminary flashover thresholds for the insulators tested in this study. PD levels vary significantly for different insulators with the same voltage and scenario suggesting that PD levels are insulator specific;

7. The RTV coated insulator and the 66 kV composite specimen significantly suppressed LC and PD activity compared to the ceramic equivalents. This supports the assertion that silicone polymer materials effectively minimise LC and PD activity. However, their comparable flashover performance (Chapter 5) to those of ceramic equivalents suggests that other physical, chemical, environmental and/or electrical factors may have more influence on LC and PD than previously thought;

8. A standardised withstand test should be investigated so that the level of LC and PD can be observed at a constant voltage over an elapsed period of time (i.e. as the ash transitions from a dry (non-conducting) to wet (conducting) state). Emphasis should be placed on defining critical thresholds (e.g. I_h) before flashover and normalising the data to account for other influential factors such as insulator material, profile, dimensioning, etc. which may contribute to the levels of LC and/or PD, irrespective of contamination severity.

Aspects of the size and location of the transmission system itself will be important considerations in choosing whether to monitor system insulators for increased or abnormal levels of LC and PD. ESDD, NSDD and/or resistivity methods represent comparatively low-tech pollution severity measuring techniques, which can be applied locally, easily and relatively inexpensively. However, more sophisticated real-time methods such as LC and PD monitoring could be justified for extensive transmission networks in developed countries where a high reliability of supply is needed to maintain the functionality of critical infrastructure and the health and safety of communities. The underlying process of flashover is stochastic, and the magnitude of the LC at any chosen time cannot be precisely predicted, however, with further investigations and analysis, the LC and PD methods investigated here have the potential to provide some warning to system operators of imminent flashover and thereby enhance the capacity to mitigate flashover during ashfalls.

6.6 ACKNOWLEDGEMENTS

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Chapter 7

Discussion and Future Research

The aim of this thesis was to investigate the vulnerability of electric power systems to volcanic ashfall hazards. The research extended the work carried out by other studies (e.g. Nellis and Hendrix, 1980; Blong, 1984; Matsuoka et al., 1995; Johnston, 1997; Bebbington et al., 2009; Wilson et al., 2009) and considered changing requirements since these original investigations were undertaken. Using traditional scientific and engineering methods informed by international technical standards, this thesis quantified and, in turn, has contributed to reducing the vulnerability of electric power systems to volcanic ashfall hazards by:

- Identifying and compiling information on the common impacts to electric power systems during and after volcanic ashfalls (Chapter 2);
- Developing a first-order fragility curve (hazard intensity/damage ratio) to relate the probability of ash-induced insulator flashover with increasing thicknesses of wet or dry volcanic ash (Chapter 2);
- Quantifying the chemical, physical and electrical properties of volcanic ash which are most influential in promoting electrical conductivity and therefore flashover on HV insulators (Chapters 3 and 4);
- Exploring the causes and mechanisms of ash-induced flashover by measuring the minimum flashover voltage and dielectric strength of commonly used outdoor high voltage (HV) insulators intended for alternating current (HVAC) systems subjected to a range of contaminated scenarios during artificial pollution tests (Chapter 5);
- A real-time indicator of the hazard (pollution) severity was studied to monitor fundamental frequency leakage current (LC) and partial discharge (PD) pulses during contamination tests (Chapter 6).

Each of the body chapters in this thesis (Chapters 2-6) has its own discussion and conclusions section. This chapter puts these discussions into context and is split into four parts. The first identifies the elements at risk of ashfall impacts specific to the 3 components of a modern power system. The second examines the application and practicality of risk assessment methods developed in the thesis to assess the flashover hazard intensity at the onset of ashfalls. Recommendations for system planning and design to reduce the vulnerability of power systems during ashfalls are provided in part three and, finally, the chapter ends with specific suggestions for future avenues of research which will strengthen the results found herein.

This thesis is a significant contribution to the fields of volcanic risk management and electrical engineering. Its findings will contribute to the readiness, response and recovery protocols for large electric power systems in volcanic disasters; which directly affects the functional operation and economics of industrial and commercial society. The vulnerability curves together with critical resistivity, equivalent salt deposit density (ESDD), non-soluble deposit density (NSDD), and creepage coverage values established within the thesis are benchmarks with which system operators can assess the flashover hazard during ashfalls. Thus, this thesis will be of direct benefit to relevant industries, institutions and vulnerable communities not only in New Zealand, but internationally.

7.1 IDENTIFYING THE RISK

The first phase of holistic volcanic risk management is risk identification (Blong, 2000). This thesis has shown that electric power networks are particularly vulnerable to disruption during ashfalls, and ash-induced insulator flashover is the most common failure mode across all sectors of the modern power network (Figure 7.1).

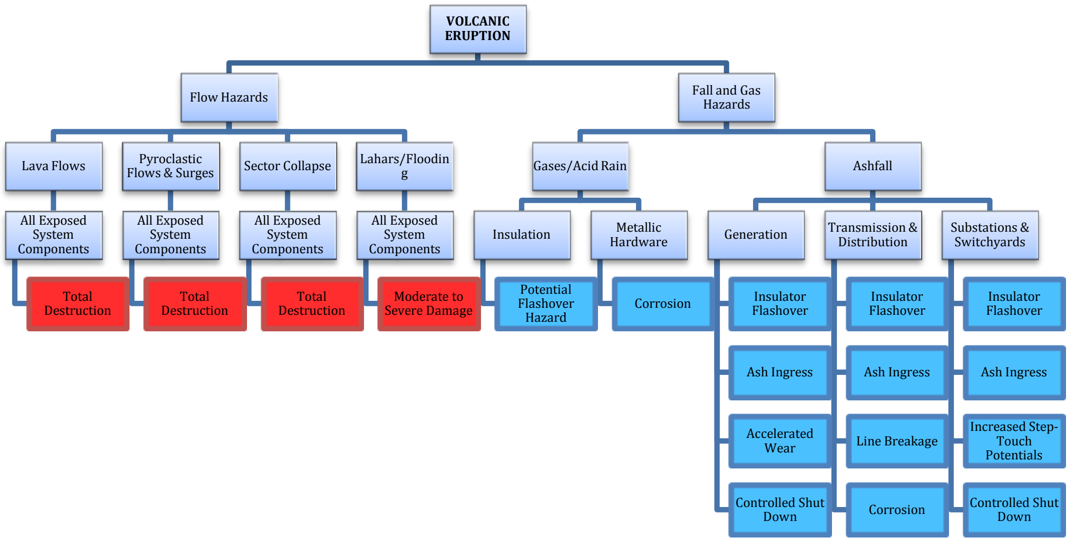

Figure 7.1: Flow chart diagram showing the potential impacts to electric power systems from volcanic hazards. Red colours signify immediate/short-term impacts while blue colours indicate possible latent/long-term effects.

7.1.1 Generation

Generation sites (hydroelectric, thermal, nuclear, etc.) are crucial to the power delivery process as the loss of generation renders the rest of the network (e.g. transformation, transmission, distribution, etc.) inactive. In general, generation facilities are vulnerable to the following impacts:

1. Insulator flashover at generation yards containing step-up transformers could lead to a series of cascading impacts on the rest of the system. The decision to shut-down a site will depend on the acceptable level of risk as determined by system operators. Cleaning methods outlined in Chapter 2 will help reduce the flashover risk and minimise de-energised time, and therefore incurred costs.
2. Ash ingress can block air intakes causing a reduction of air intake quality and quantity for turbines and cooling and heating, ventilation and air-conditioning systems at generation sites and substations (Chapter 2).

The most common disruptor of power at hydroelectric power generation sites is controlled shut-down of turbines to avoid accelerated wear of submerged components. In the event of volcanic material entering feed water, careful and constant monitoring of ash properties (e.g. angularity, hardness, soluble salt load, etc.) and water conditions (e.g. turbidity, pH, etc.) should inform the risk management decision to shut-down or maintain operations. Alternatively, depending on the degree of ash-settling in the HEP reservoir, plants with an in-take bypass system may choose to re-direct ash-rich water away from vulnerable elements.

Nuclear sites are not explored in this thesis, however they may require considerable time to shut-down sensitive system components, such as reactors. The decision to stop operations at these facilities will require prompt and decisive action as improper crisis management could lead to significant reduction in plant functionality which leads to social and economic consequences. The devastating March 2011 Tohoku earthquake and tsunami is a pertinent example, when the resulting loss of off-site power initiated catastrophic event sequences which severely damaged the Fukushima-daiichi nuclear power station (Anzai et al., 2011).

7.1.2 Transmission and distribution

Transmission and distribution systems are most vulnerable to volcanic ash-induced insulator flashover. Flashovers have been recorded during relatively small ashfalls (e.g. 3 mm during Ruapehu 1995/96). However, smaller deposits (≤1 mm) may have sufficient conductivity (ESDD) and NSDD to cause outages, provided a significant portion (>60% as reported in Chapter 5) of the protected creepage distance is contaminated with ash (Chapters 3, 4 and 5).

The risk associated with minor deposits of ash (<3 mm) on the top surface of insulator sheds may be retained by informed decisions to leave ash to be cleaned by rain and wind action (Chapters 2 and 5). If wetted, however, fine-grained volcanic ash (<0.5 mm particle diameter) can strongly adhere/cement to insulator surfaces. Even if the soluble material has been leached, the high NSDD of volcanic ash can pose a latent risk of flashover (Chapter 3), as the residual deposit will retain subsequent moisture (e.g. rain, fog, mist, dew, etc.) which has an inherent conductivity (Chapter 2).

Conductive (i.e. wet) ash deposits will cause tracking of current and corrosion and may burn and/or etch the glazing of ceramic insulators. Over time, these small cracks and voids will grow and may eventually lead to puncture of the insulator (Rawat and Gorur, 2009).

Ash-laden foliage will not make contact with conductors, bridge phases and/or cause line breakages provided trees are pruned to meet appropriate/normal clearance distances from operating transmission and distribution lines.

7.1.3 Substations and switchyards

Past experience has shown that prompt shut-down and cleaning of substations will maintain the integrity of the power system, which suggests it may be the most appropriate action, despite some intrinsic system/functional, and thus economic, loss. Even minor ashfalls (≤1 mm) can result in outages, and the evaluation of acceptable risk will vary between system operators. As substations and generation sites are crucial to the continuity of supply, immediate risk assessment for these facilities at the onset of ashfall is paramount.

7.2 ANALYSING AND EVALUATING THE RISK

Analysis and evaluation stages of the risk management process within this thesis focussed on developing an understanding of the potential risks and impacts to specific power system elements from volcanic ashfall hazards. Impacts can range from minor nuisances such as increased audible noise from contaminated conductors, to major physical damage to critical components such as HEP turbines. Given insulator flashover is the most common impact, four quantitative forms of analysis were developed to analyse and evaluate the flashover risk at the onset of ashfall, and are discussed in the following sections.

7.2.1 Electrical properties of volcanic ash

The electrical characteristics of volcanic ash are important controls on the ash flashover mechanism. Prior to this thesis, very little empirical data existed on the physical, chemical and electrical parameters of volcanic ash most influential in initiating ash-induced impacts such as insulator flashover.

Well-established in the field of power engineering, ESDD and NSDD measurements produce valuable parameters for comparative purposes. The existing knowledge makes it an easily relatable measurement of hazard intensity for system operators and decision makers. For example, a uniform 3 mm layer of volcanic ash on a HV insulator causes moderate to heavy pollution severity, and even light dustings (<0.5 mm) can be severe enough to significantly reduce the performance (flashover voltage) of HV insulators (Chapter 5). This highlights the high risk of volcanic ash contamination to the reliability of power supply.

However, through the course of this thesis it was realised that the ESDD/NSDD method has several inherent limitations (Chapter 3) which make it unsuitable as an in-field mode of hazard intensity assessment. Primarily, the ESDD method does not account for the variations in electrical conductivity of the ash under different environmental, chemical and physical conditions, and the limited amount of data available for pollution with NSDD levels >4 mg/cm^2 inhibits IEC 60815-1 (2008) pollution severity classification. Thus, a resistivity method was developed to measure the electrical properties of volcanic ash as an alternative to ESDD and other pollution monitoring techniques (Chapter 3).

Resistivity analysis of volcanic ash samples is appropriate for small volume, rapid in-field analysis. If calculated early enough in the eruption, resistivity values can be compared to the database, started in Chapter 3, to dictate whether the ash is conductive enough to cause flashover. Areas with the highest risk of flashover can be identified from isopach maps (lines of equal ash thickness) and specific assets or elements within those zones targeted for mitigation, if necessary. Combined with fragility function estimates particular to system elements/apparatus, a robust impact forecast can be generated. Persistent monitoring of ash properties (e.g. resistivity, ESDD/NSDD), live-line diagnostics (e.g. PD and/or LC), and the depositional patterns on HV insulators (e.g. % creepage coverage) will also be key steps in avoiding ash-induced impacts and minimising economic losses from unnecessary controlled outages.

7.2.2 Forecasting flashover using fragility functions

There is an increasing desire to use quantitative risk assessment methods to express power system vulnerability to volcanic hazards to define the risk posed by current or future volcanic events, and to better account for evolving eruption histories, incomplete and/or short eruption histories, and volcanoes with a range of possible future eruption magnitudes and/or styles (Smith, 2004). This may be achieved through further analysis of data in this thesis and future analogue laboratory experiments and field observations. This thesis provides a foundation for future vulnerability assessments during ashfalls. For example, using the fragility function proposed in Chapter 2, system operators can rapidly approximate the flashover risk on HV insulators. The vulnerability estimate is complemented by other analyses such as ESDD/NSDD, which define the ash's electrical properties, and therefore hazard intensity.

While the first-order fragility function in Chapter 2 provides a basis for flashover risk assessment, the function is limited by a binary, discrete end-member data set and a lack of hazard intensity parameters. However, power-frequency test results in Chapter 5 can be used to refine the model. Although speculative, the following fragility models are informed by published work on volcanic ash impacts to electrical infrastructure (Chapter 2), anecdotal information from experts in the fields of volcanic hazards and electrical engineering, observations made of the impact of insulator flashover during the 2010 eruptions of Tungurahua (Ecuador) and Pacaya (Guatemala) volcanoes (Appendices 1 and 2, respectively), as well as results and observations from this thesis. These are best-guess estimates which represent the current state of knowledge on some of the more important factors promoting volcanic ash-induced flashover. Further development of these and other vulnerability models for power system equipment and apparatus will undoubtedly strengthen the reliability and efficiency of system response protocols during volcanic ashfalls.

This thesis suggests that, for a standard porcelain insulator operating during ashfall in low wind conditions and light, misty rain, significant (e.g. >3 mm) ash deposits can accumulate on the top surface of insulator sheds without significantly reducing the flashover voltage (i.e. increasing the flashover potential), as long as the underside (bottom) surface remains clean and/or dry (Figure 7.2a). Since the bottom surface of the porcelain insulator contains the majority of creepage distance (~75%), and assuming a uniform coating of wet ash, the probability of flashover will increase significantly with increasing ash thickness on the bottom surface of the insulator (Figure 7.2b). Empirical evidence in this thesis therefore suggests that ash thickness alone is not an adequate measure of hazard intensity for forecasting the likelihood of insulator flashover, since several other environmental, volcanological and electrical factors will influence the insulator's flashover voltage.

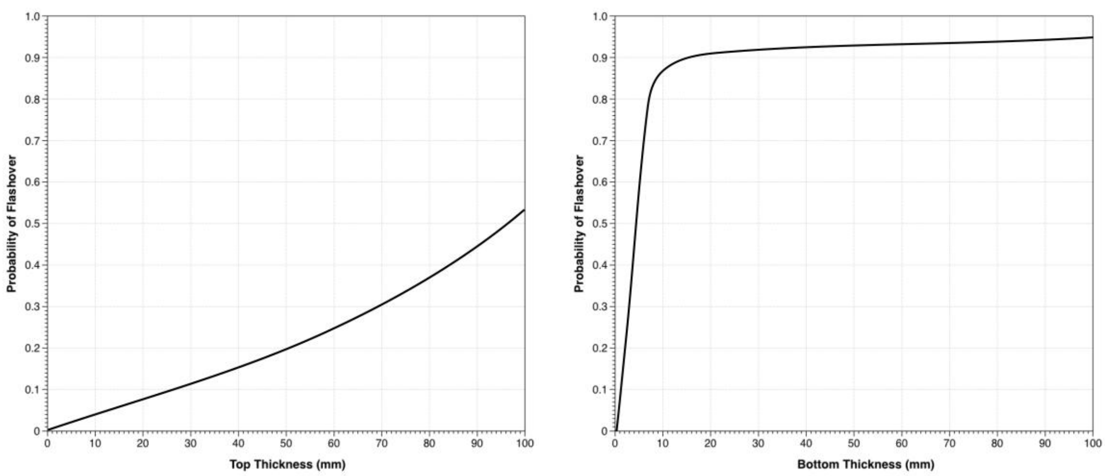

Figure 7.2: Preliminary fragility functions relating the probability of insulator flashover to **a)** ash thickness on top surfaces only, and **b)** ash thickness on the bottom surface.

As creepage distance is the primary parameter responsible for reducing the flashover voltage, and therefore pollution performance of the HVAC suspension insulators used in this thesis (Chapter 5), it may be a more useful indicator of imminent flashover. Based on the 30% critical creepage coverage estimate made by Nellis and Hendrix (1980) and the 60% proposed in Chapter 5, Figure 7.3a illustrates a hypothetical model relating probability of flashover to increasing coverage of creepage distance. The ability of volcanic ash to cover protected creepage distance will be dependent on insulator material, orientation, and profile (discussed further in Section 7.3.3). Similarly, considering the environmental controls and pollution ranges for standard porcelain tests in Chapter 5, the numeric relationship between ESDD/NSDD and the probability of flashover is hypothesised in Figure 7.3b.

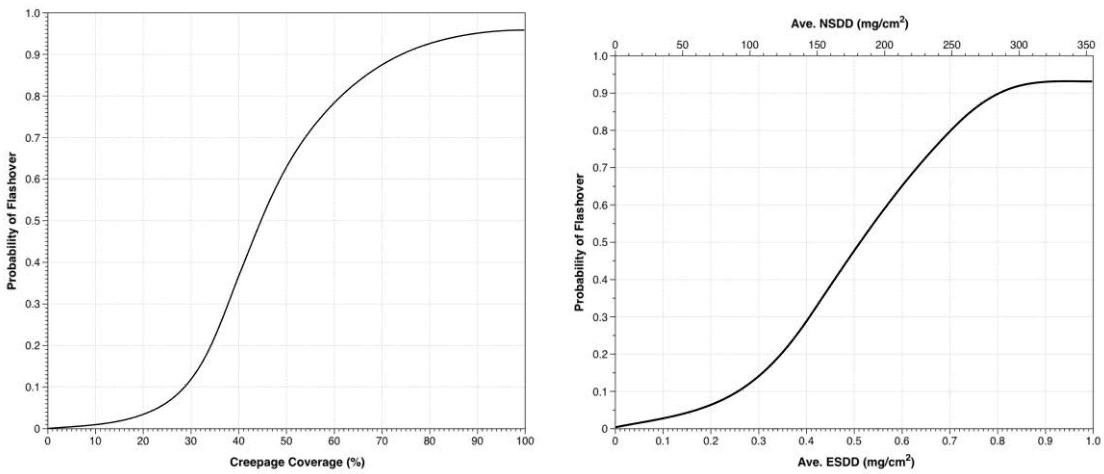

Figure 7.3: Preliminary fragility functions relating the likelihood of insulator flashover to **a)** coverage of the protected creepage distance, and **b)** average ESDD/NSDD based on those obtained for the pseudo ash.

7.2.3 Leakage current and/or partial discharge analysis

Existing literature highlights the potential of fundamental frequency LC monitoring to indicate critical contamination levels on energised HV insulators (Farzaneh and Chisholm, 2009). Exploratory experiments in Chapter 6 showed that, due to current-voltage proportionality, sinusoidal power-frequency LC increases with increasing applied voltage and large current surges due to partial arcing and discharges (e.g. a range from 26 mA recorded for the standard glass insulator to 136 mA for the aeroform specimen) will occur once critically contaminated conditions (e.g. complete surface area coverage) are reached. It is therefore expected that measuring the temporal change (increase) in current amplitudes (I_h) during ashfalls would be an effective indicator of impending flashover.

A novel, real-time method for monitoring volcanic ash pollution severity on energised insulators using PD analysis was also proposed in Chapter 6. PD pulse magnitudes increase with increasing voltage but vary with contamination severity (e.g. wet or dry ash). While results indicate that several physical and environmental factors may influence PD, the summary plots presented in this thesis represent critical PD levels prior to insulator flashover for a range of ash contamination scenarios. Further refinement of the LC and PD analyses investigated in this thesis could provide a robust real time method for monitoring system response to increasing ash contamination.

7.3 REDUCING THE RISK

During an ashfall, the decision to reduce the risk of impacts by implementing mitigation strategies will depend primarily on the: (1) predicted area and volume of ash dispersal (isopach maps produced by volcanic scientists), (2) specific assets exposed to ashfall and their relative importance to maintaining system integrity, and (3) electrical properties (pollution severity) of the ash. Adequate hazard assessment and identification and quantification of system vulnerability at the onset of ashfall will provide a robust indication of the risk.

Volcanic eruptions will vary in intensity and duration (seconds to decades) with each eruption. As a result, power system apparatus may be exposed to variable and potentially prolonged periods of ashfall. This becomes a critical design parameter for transmission or distribution circuits situated in historic fallout zones and will be an important consideration for lines requiring refurbishment or retrofitting to cope with frequent ash contamination in the short or long-term. The following sections discuss some of the important short and long-term considerations for system design, and the criteria for selection of insulators with respect to volcanic ash contamination.

7.3.1 Short-term: Planning for ashfalls

Whilst it is not possible to completely eliminate the risk of impacts, emergency management (response) protocols should be established to maintain system integrity during volcanic ashfalls. Chapter 2 provides a preliminary response plan by which system operators can be guided when faced with the decision to maintain or cut power delivery to vulnerable sections of the network. Such decisions will benefit from situational awareness by actively monitoring warnings and advice from local volcano observatories or relevant agencies to obtain the most up-to-date scientific alert levels, eruption warnings, ashfall maps and forecasts.

Figure 7.4 illustrates the role of this thesis in guiding the emergency response of power engineers and volcanic risk scientists through the identification, assessment, and reduction of risk from ashfall hazards during future eruptions. Critical hazard intensities identified herein, such as ESDD/NSDD, resistivity, LC and/or PD, are important indicators of the likelihood of component failure and should be quantified immediately in order to assess the level of risk. Based on the mitigation strategies proposed in this thesis, power engineers have a number of potential risk reduction actions through system design, maintenance, and/or palliative methods. Partnership and knowledge transfer between volcano hazard scientists and power engineers in identifying assessing and reducing the risk of impacts is crucial to effective risk reduction. In many instances, it may be more cost effective to develop response plans with a focus around shutting down versus maintaining operations, however, the decision to maintain operations will be dictated by the level of acceptable risk as dictated by the system operator(s).

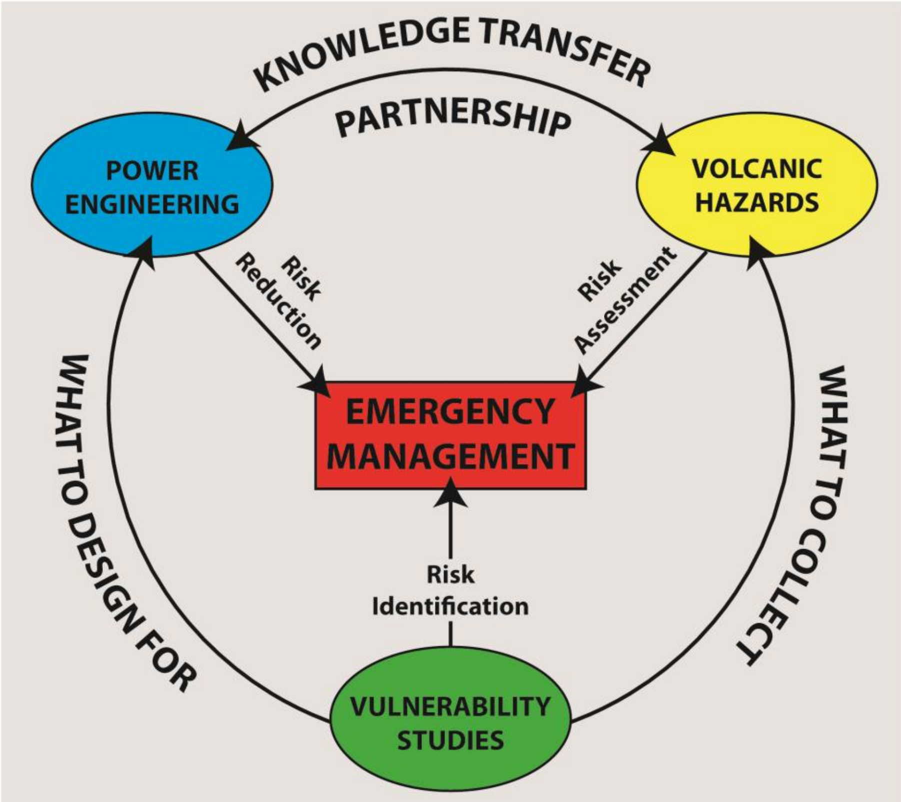

Figure 7.4: Schematic diagram illustrating the role of vulnerability studies such as this thesis in guiding the emergency management response of power engineers and volcanic risk scientists through identification, assessment, and reduction of risk from ashfall hazards during future eruptions.

Cleaning ash from critical system components such as generation sites and substations has been identified as an effective short-term treatment for reducing the risk of ash-related impacts (e.g. flashover, transformer overheating, reduction in resistivity of substation gravel, etc.) (Chapter 2). Both offline and online cleaning methods for volcanic ash contamination on station and line insulators were described in Chapter 2 (and are discussed further in Section 7.3.3.1). These methods and those detailed in IEEE Std 957 (2005) may be easily adapted for other system elements.

7.3.2 Long-term: System design

7.3.2.1 Land-use planning

Constructing a power system completely tolerant to ashfall hazards is economically and logistically impractical. An obvious way to minimise system vulnerability is to avoid the risk altogether by choosing not to place system assets in areas exposed to a high ashfall hazard. Despite being an extreme measure, revising land-use planning is an effective means of reducing system vulnerability, particularly for areas prone to frequent ashfalls. With further quantification of specific component vulnerability to ash-induced impacts, and a cost-benefit analysis, acceptable levels of risk may be identified to better advise system expansion into these zones.

7.3.2.2 System redundancy

Critical system elements such as power transformers typically have a high capital cost, and can have long manufacturing lead times. Thus, unless the power system has been designed to include a sufficient level of redundancy, ash-induced damage to such apparatus may result in long-term outages and significant economic loss. As mentioned in Chapter 2, power systems are often designed to be 'N-1 secure' because it can cope with losing any one of its N components and continue to carry the demand load. In recent years, the North American Electric Reliability Corporation (NERC) has increasingly recommended retrofitting of systems to be N-2 or N-3 secure (NERC TPL Std, 2005). While N-1, N-2 and even N-3 secure systems reduce the potential for loss of supply, they do not consider the far-reaching effects of ash, which can cause numerous faults on multiple system components over hundreds of square kilometres. Thus, cost-benefit analysis and risk assessments for assets with an unacceptable level of vulnerability should dictate the level of redundancy necessary to maintain functionality during ashfalls.

7.3.3 Insulator selection for areas with a high ashfall hazard

The performance of an insulator depends on complex interactions between it and the operating environment and ample information exists on the appropriate selection, dimensioning and maintenance of HV insulators intended for use in outdoor AC transmission systems (e.g. IEEE Std 957, 2005; IEC 60815-1, 2, 3, 2008; IEEE Std 516, 2009; IEEE Std C62.82.1, 2010). This thesis has shown that, in general, there are two principal design criteria for HV insulators with respect to volcanic ash contamination: profile (shape) and dimensions (Figure 7.5).

The profile of an insulator will influence the rate and degree (pollution severity) of contamination. For example, intricate designs such as anti-fog or fog-bowl profiles can generate vortexes and wind flow patterns which may result in increased ash adherence. In turn, this could (1) lead to localised arcing and, consequentially reduce the effectiveness of these profiles, and (2) make cleaning more difficult during and/or after ashfalls. Other external environmental, volcanological and electrical influences such as wind speed, particle size, static charge and/or dielectrophoresis will directly affect the adherence of volcanic ash to insulator surfaces. Additionally, other insulator design parameters such as material, orientation and the amount of protected creepage distance exposed to fallout will also play a role. Insulator profile will influence the ability of moisture (e.g. rain) to wet insulator surfaces. Light rain, fog, dew, drizzle, etc. will not wash the ash off the insulator but will dissolve attached soluble salts and render the deposit conductive. The intensity of rain will determine whether the ash is wetted or washed away and, similarly, high winds will remove ash from the insulator.

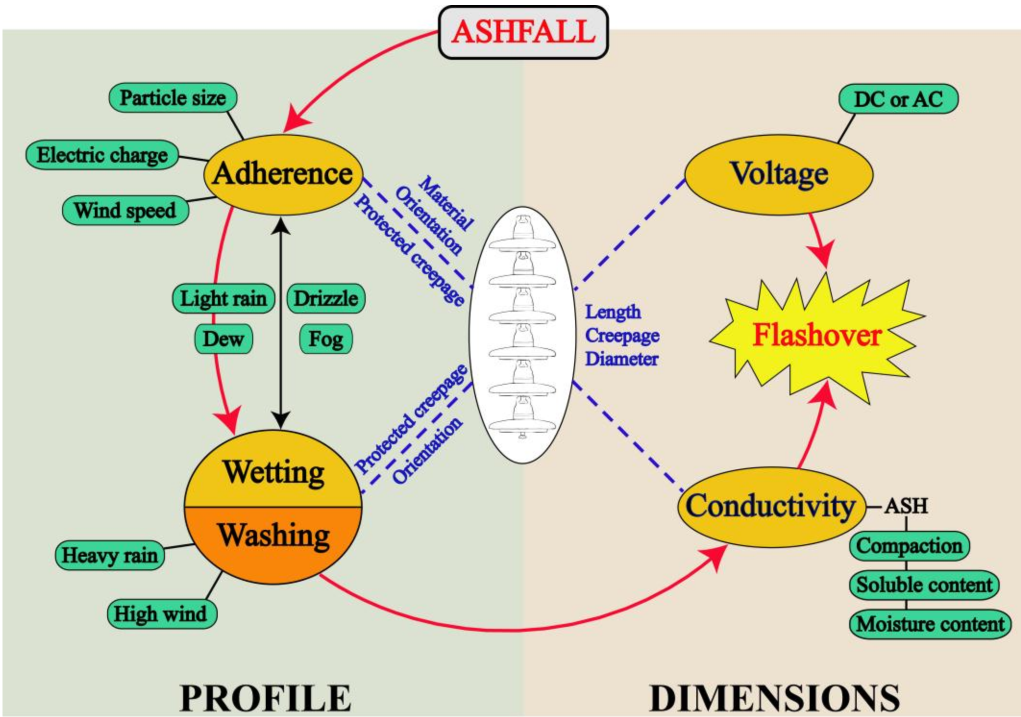

Figure 7.5: Schematic diagram showing how the profile and dimensions control the process of ash-induced insulator flashover. Additional environmental, volcanological and electrical parameters most influential in causing ash-induced insulator flashover are also presented to show the many factors contributing to the flashover mechanism.

Results from this thesis suggest that three design dimensions control the performance of an insulator: overall length (dry arc distance), creepage distance, and shed diameter (Chapter 5). These parameters regulate the amount of exposed surface area to ashfall and will control the extent of surface conductivity. The volcanological parameters most influential in controlling ash conductivity are the degree of compaction (bulk density), soluble content (ESDD), and moisture content of the ash (Chapter 4). High surface conductivity and the AC or DC electric field (induced by the operating voltage) will initiate a leakage current. Arcs will grow with increasing dry band zones and will ultimately bridge the entire insulator, causing flashover (Chapter 5).

Considering the aforementioned processes, the ideal insulator for volcanic ashfall zones is therefore one with an appropriate balance between profile and dimensions, where maximum creepage distance is achieved in a profile with good self-cleaning properties. While not analysed in this thesis, high creepage designs such as fog or bowl-type insulators are expected to perform as well or better than the suspension specimens analysed in Chapter 5. The polymeric long-rod insulator tested in this study showed the highest dielectric strength across the majority of contamination scenarios and generally outperformed the ceramic comparators (Chapter 5). Polymeric insulators are therefore considered the optimal insulator material for HV circuits located in zones with a high ashfall hazard.

7.3.3.1 Palliative measures for insulators at risk

IEC 60815-1 (2008) provides several potential palliative measures for HV insulators intended for use in heavily polluted environments. Table 7.1 places these risk treatment options into the context of volcanic ash contamination and, based on experimental results and observations from Chapter 5, assesses the capacity of these methods to mitigate ash-induced insulator flashover.

Table 7.1: Potential of the recommended IEC 60815-1 (2008) palliative measures for mitigating volcanic ash-induced insulator flashover.

Increase creepage distance	Our results suggest that, of the insulators tested, so long as ~60% of the overall creepage distance is protected from wet ash contamination, the V_{50} of will not be reduced to a level which would compromise system integrity. Thus, increasing creepage distance for insulators situated in areas receiving frequent ashfalls may be a simple and effective means of reducing the flashover risk.
Non-ceramic insulators	Results from this thesis support the assertion that non-ceramic insulators generally outperform ceramic designs (IEEE Std 987, 2001). However, there are a number of chemicals that may degrade polymer materials and cause swelling or even de-polymerisation (Farzaneh and Chisholm, 2009). Over 55 soluble components have been measured in volcanic ash leachates (Witham et al., 2005). Thus, the influence of these volcanogenic solubles on the hydrophobicity and overall pollution performance of composite polymer insulators warrants further investigation.
Washing/ cleaning	If changing the creepage distance alone does not sufficiently improve the pollution performance of an insulator, then scheduled washing by field crews and/or fixed nozzles may be a viable alternative (e.g. Yasuda and Fujimara, 1976; Cakebread et al., 1978). In particular, substation insulators may benefit from regular washing following volcanic ashfalls, especially if remobilised deposits are an issue.
Hydrophobic coatings	This thesis has shown that a standard glass suspension insulator coated with a layer of RTV coating performs ~5-10% better than that of an unmodified specimen when polluted with light to moderate ash pollution severities. However, under heavy contamination (e.g. ash on top and bottom of insulator sheds), the treated insulator's performance was equivalent to that seen in other specimens, suggesting that little benefit is to be gained from its implementation. Hydrocarbon and silicone greases are not recommended for mitigation against ash contamination as, after a few years of service, the majority non-soluble component in volcanic ash will saturate the grease, requiring removal and reapplication (IEEE Std 1313.2, 1999).
Semi-conductive glaze insulators	The surface of semi-conductive glaze insulators is made of a thin layer of resistive glaze. The semi-conductive coating initiates a low-level leakage current which heats the insulator surface, preventing condensation and wetting. However, lab and field experience suggests that the main failure mechanism for semi-conductive glaze designs is extremely high pollution conditions (e.g. ESDD >1 mg/cm^2) (Farzaneh and Chisholm, 2009). Nevertheless, this strategy may be applicable to volcanic ash contamination if (1) the wetting rate does not exceed the evaporation rate of the ash layer, and (2) contamination levels (ESDD/NSDD) of volcanic ash are sufficiently low so as to not cause excessive power dissipation.
Installation of additive components	While this thesis has focussed on suspension insulators, some mitigation applications have been devised for other insulation designs, such as those at substations. Booster sheds were first developed to improve insulator performance under heavy rain conditions (Ely et al., 1978) and are commonly designed as a flexible rubber shed which slips around a post insulator (or bushing, surge arrestor, etc.). Similarly, creepage extenders are designed to reduce the problem of pollution-induced flashover by increasing the shed diameter and therefore creepage distance of station insulators (Metwally et al., 2006). Both measures have potential to improve the volcanic ash performance of insulators, however, more research is needed to investigate this.

7.4 FUTURE DIRECTIONS

In general, future research should continue to explore the vulnerability of electric power systems to volcanic ashfall hazards, particularly to those elements which are critical to the continuity of supply (e.g. power transformers) or require long shut-down times (e.g. nuclear facilities). Systematic documenting of the direct, indirect and intangible impacts should continue as part of holistic vulnerability analysis.

Further research should be devoted to the following areas (detailed in the subsequent sections):

- Repetition, expansion and standardisation of artificial pollution (volcanic ash) tests for HVAC insulators to augment the data collected for this thesis;
- Detailed and standardised reporting of power system failure and tolerance during and/or following ashfalls to (1) improve our understanding of the processes of ash-induced impacts, (2) enhance the effectiveness of methods used within probabilistic volcanic risk assessment, and (3) inform emergency response planning and mitigation strategies;
- Statistically derived scenario building and power system modelling to identify vulnerable components for future ashfalls.

7.4.1 Augmenting flashover data

Due to limitations in test power supply and equipment available during the rapid flashover tests, more data would augment the results and findings herein. Future contamination tests should include both rapid flashover and withstand measurements, be carried out in a fog chamber, use a test supply with a short circuit current >6 A, and investigate a range of insulator orientations, materials, and profiles. This will ensure the reproducibility of results in other laboratories.

The unusually high NSDD of volcanic ash makes it very different from typical airborne pollution. Thus, very little comparable flashover voltage data exists. Continued development of pollution performance curves for different insulators will inform the selection of appropriate models and strengthen the predictive capacity of vulnerability estimates (e.g. fragility functions). To create a more realistic outdoor scenario within the lab, an ash dispenser designed to simulate ashfall onto an insulator energised to its rated voltage should be considered. This would provide a more accurate means of identifying the critical contamination thresholds before flashover.

7.4.2 Data collection practise

There remains a need for standardised electrical testing protocol for freshly fallen/falling volcanic ash. In order to be effective, information for operator decision support must be provided immediately and from as many different localities as possible, to show how ash might vary in conductivity and other hazard intensity measures with place and time. If information regarding the pollution severity of the ash is known at the onset of ashfall, an operational response model which utilises damage estimates (forecasts), ground impact assessments, and insight on critical contamination conditions from this thesis could be initiated to reduce the potential for loss or damage. Critical infrastructure (e.g. transportation, water and waste water systems, telecommunications, etc.) and services (e.g. hospitals, schools, etc.) could also be targeted and advised to initiate their own emergency response plans (e.g. shutting-down, shedding load and/or switching to backup power, etc.) to minimise societal effects.

One way to obtain rapid electrical data would be a monitoring scheme similar to that of New Zealand's GEONET (Ground-based Earth Observing Network) system for earthquakes. Preferably, given the relative simplicity of the methods used here, locals could be instructed how to take their own ESDD/NSDD and/or resistivity measurements which could then be relayed to scientists, engineers and/or hazard managers. Alternatively, the general public could collect ash following specific guidelines, and send in the samples for analysis. However, no single technique is the most appropriate for all situations and a range of low-cost, rapidly dispatched measures will likely provide the best results.

7.4.3 Cascading failure and/or common-mode outages

More research is needed to estimate the potential for cascading effects and common-failure mode outages induced by volcanic ashfall hazards. Due to the vast number of services which require electricity, large blackouts initiated by volcanic ashfalls could have disastrous consequences. Given the absence of large-scale power loss from ashfall in recorded history, there is a general lack of awareness for the likelihood of such an event (e.g. Hines et al., 2009). A set of two or more nearly simultaneous outages can initiate cascading failures and, as discussed in Chapter 2, volcanic ashfalls can trigger a series of events, eventuating with either the shut-down of one or more components or multiple outages across the power system within a short space of time.

Power system modelling and statistical development of the most likely eruption scenarios will help to understand the holistic effects that numerous ash-induced impacts and interactions may have on the power network and on other public infrastructure systems (Entriken and Lordan, 2012). For example, estimates of the most likely eruption scenarios and areas of ash fallout could be devised from historic eruption behaviour (i.e. magnitude) and recurrence intervals. Depending on the conditions set by each eruption scenario and the potential range of impacts from ash contamination, power system modelling can assess the loading on major components of the power system and then identify the most likely failure modes during future events.

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Appendix 1: Infrastructure impacts, management and adaptations to eruptions at Volcan Tungurahua, Ecuador, 1999-2010

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Mr. Wardman is second author to Ms. Victoria Sword-Daniels. Dr. Carol Stewart, Dr. Thomas Wilson, Dr. David Johnston and Dr. Tiziana Rossetto are also co-authors. Mr. Wardman, Ms. Sword-Daniels and Dr. Stewart contributed equally to the writing process and Dr. Wilson, Dr. Johnston and Dr. Rossetto refined the manuscript through in-depth reviews.

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- In cases where the PhD candidate was the lead author of the co-authored work he or she wrote the text.

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Appendix 1

Infrastructure impacts, management and adaptations to eruptions at Volcan Tungurahua, Ecuador, 1999-2010

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Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010

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ABSTRACT

This report summarises observations made on a field visit to areas affected by the May 2010 eruption of Volcán Tungurahua, Ecuador. The focus of this trip, carried out in September 2010 by a field team from the University of Canterbury and University College London, was to investigate both direct and indirect effects of ashfall on critical infrastructure, and the management of ashfall events. In particular we paid attention to less-studied areas of interest including electrical power and healthcare systems. All infrastructure topics explored aspects of resilience and adaptation, in the context of ongoing volcanic unrest at Tungurahua since 1999. Research methods were largely qualitative and included semi-structured interviews, observation, water testing and informal conversations and meetings with locals.

A good overview of ashfall impacts on electricity networks, healthcare services and emergency management issues was achieved during the trip. The information gathered adds to our knowledge of the possible effects of volcanic ashfall on infrastructure and public services. Further insights into impacts of water, wastewater, transportation and agriculture were gained.

Overall, infrastructure seemed to function well during the 2010 eruption, with only minor problems reported. However, the May 2010 eruption generated only minor ashfalls (a few mm) in most locations. Over the past 11 years of volcanic unrest, other events have caused more serious impacts, particularly a VEI 3 eruption on 16-17 August 2006.

Electrical supplies suffered few problems, with no reports of electrical flashover from ashfalls. Problems arising from contamination of open water supplies have led to an initiative to cover water supplies. In the transport sector, the 2010 eruption resulted in a two-day closure of Guayaquil international airport due to risks to aircraft. Roads in the Tungurahua region have been frequently damaged by lahars over the past 11 years. The 2010 eruption caused partial damage to 3740 ha of crops. Far more severe, although localised, damage to crops, livestock and rural communities was caused by the August 2006 eruption.

Healthcare centres are well-organised and are able to prioritise essential services in the event of an ashfall, and so experience few major impacts, but a variety of minor impacts on facilities and equipment. A variety of public health pathologies have increased by small amounts in the short term after ashfalls, and psychological impacts in communities affected by eruptions have increased since activity began at Volcán Tungurahua in 1999, and have required increased attention from healthcare professionals in the long term. Emergency management insights provide lessons pertaining to the benefits of local engagement and involvement in risk management, including the influential role of the vigìas, who act as observers of volcanic activity and coordinators of voluntary civil defence within the community.

The focus on adaptations and responses to the long-term volcanic activity has provided insights into the long-term effects of volcanic activity and helped identify possible mitigation and prevention measures. It is found that in general, increased maintenance of infrastructure now occurs widely across sectors, and cleanup methods for specific sectors have been developed to cope with ashfalls. The cleanup of ash at the municipal level is well organised, and is coordinated with the National Secretariat of Risk Management such that costs are shared with the proportions adjusted according to the severity of the situation. Increased use of personal protective measures (such as masks and goggles) has achieved a reduction in

public health impacts. Healthcare centres are also well organised, forming brigades for rapid response in affected areas, and having a clear hierarchy of health centres within each region so that patients can be transferred if necessary. They have good knowledge of the volcanic alert level system and the protocols required for each alert level change. Emergency management also appears organised. Emergency drills are run in at-risk communities, and contingency plans are updated and revised following eruptions. Hazard warning and shelter signage is also widespread in the Tungurahua volcanic hazard area.

Overall, we found clear evidence for increased organisation and improved management procedures in the Tungurahua volcanic hazard area, which should have strengthened societal resilience. Additionally individual adaptive behaviour has included: increased use of personal protective equipment, which has reduced public health effects; farmers growing more ash-resilient crops including onions, and using greenhouses for crop growth; farmers only rearing livestock for a shortened period of time in the area, in order to prevent tooth abrasion; and an initiative to cover water supplies to protect them from contamination by ashfalls.

Other examples of adaptations to infrastructure have included: widespread hazard signage; sirens in and around Baños for early warning (with an alternate power supply in case of power cuts, and a contingency emergency services siren system); floodgate design at Agoyan dam for bypassing turbulent water; and the development of plans to relocate electrical transmission towers away from valleys that have, in the past, been affected by lahars.

Further studies in the Tungurahua volcanic area would be beneficial, to gain long-term understanding of volcanic ash consequences on a variety of sectors, including those explored in less depth in this study.

KEYWORDS

Volcán Tungurahua, eruption, ashfall, infrastructure, impact, resilience, adaptation.

1.0 INTRODUCTION

Ecuador is a country at risk from volcanic hazards (Table 1), with many populated areas located close to active volcanic centres and within range of volcanic ashfalls. The exposure of populated areas to volcanic ashfall warrants a greater understanding of the impacts of volcanic ash. Furthering our understanding of these impacts, to inform mitigation and emergency management procedures, is of critical importance to reducing the effects of volcanic eruptions on at-risk populations.

Table 1 Eruption frequencies for selected countries (after Wilson et al. 2009).

Selected countries	Population (2008)[1] (million)	Average eruption frequency	
		VEI[2]0-3	VEI 4-7
Indonesia	239.9	6 months	15 years
Iceland	0.3	6 years 10 months	43 years
Japan	127.7	7 months	44 years
Guatemala	13.7	4 years 9 months	53 years
Philippines	90.5	1 year 4 months	59 Years
Papua New Guinea	6.5	8 months	81 years
Alaska, Kamchatka, Kuril Islands	1.1	5 months	100 years
Ecuador	13.8	2 years 5 months	102 years
Canada, Lower 48 states USA	335.8	1 year 6 months	143 years
Italy	59.9	5 years	215 years
Colombia	44.4	6 years 6 months	304 years
Mexico	107.7	7 years 6 months	375 years
New Zealand	4.3	11 months	394 years
Chile	16.8	1 year 4 months	554 years
Nicaragua	5.7	1 year 2 months	806 years
Peru	27.9	14 years 2 months	832 years

[1] 2008 World Population Data Sheet, Population Reference Bureau
[2] The Volcanic Explosivity Index (VEI) is a classification scheme for volcanic eruptions, ranging from VEI 0-8, with VEI 0 the least explosive (Newhall and Self, 1982)

In 2004, a team from New Zealand visited Ecuador to study the impacts of volcanic ashfall on infrastructure and agriculture, and volcanic hazard emergency management. The focus of this trip was the 2002 eruption of Reventador and the eruptions of Volcán Tungurahua since 1999 (Leonard et al., 2005).

The current study has been designed to build on the findings of the previous one, and to add detail and knowledge on new areas of research on infrastructure. In particular, the aims were to further our understanding the impacts of ashfall on critical infrastructure facilities; infrastructure service provision; the knock-on effects of infrastructure lifeline disruption onto other facilities and on the public; the critical lifelines that support community infrastructure and social networks; and the progress in disaster planning and management.

This report presents and discusses findings from a study tour of the regions of Ecuador most affected by the recent May 2010 eruption, and by the previous eruptions of Volcán Tungurahua. Field work in Ecuador was carried out between 5-18 September 2010 by a team representing the University of Canterbury, Christchurch, New Zealand, and University College London, UK. For a complete trip itinerary, refer to Appendix 1.

1.1 Personnel

The field work in Ecuador was carried out by the team of: Victoria Sword-Daniels (doctoral student, University College London), Johnny Wardman (doctoral student, University of Canterbury), Carol Stewart (research affiliate, Joint Centre for Disaster Research, Massey University/GNS Science) and Fiona Woods (translation support). The wider team that supports this work also includes: Tom Wilson (University of Canterbury), David Johnston (Massey University/GNS Science), and Tiziana Rossetto (University College London). A photograph of the field team is included below.

Photograph of the field team, from left to right: Fiona Woods, Johnny Wardman, Carol Stewart, and Victoria Sword-Daniels.

1.2 Aims of the study

The following were the specific areas of interest for our study:

- Impacts on essential infrastructure (electrical supply and generation networks, water supplies, wastewater systems and transport and communication networks);
- Impacts on healthcare facilities and healthcare service provision;
- Activation of health facility emergency management plans;
- Impacts on agriculture, including livestock evacuation;
- Assessment of evacuation planning during a volcanic crisis;
- Factors affecting evacuation of communities;
- Socio-economic impacts, such as stresses and disruption due to evacuation;
- Social and physical adaptations made to living with volcanic hazards.

Due to limited field time and our research interests, it was not possible to cover all of these areas in equal depth. The topics covered in greater detail were: healthcare facilities, electrical transmission and generation sites and emergency management. Inquiry into the May 2010 eruption, together with a comparison of impacts from previous eruptions, allowed a greater longitudinal insight into the adaptations to, and the resilience of such infrastructure.

1.3 Research methods

Research methods utilised during this study trip included field observations and measurements, meetings and semi-structured interviews.

Meetings and semi-structured interviews were conducted at infrastructure offices and facilities in affected areas, using a translator to conduct the interviews in Spanish. Ethical approval for the interviews was granted from the university institutions University College London and University of Canterbury prior to leaving (see Appendix 5). Interviewees were comprised mainly of facility managers, directors and operating professionals. Organisations of interest were identified beforehand, where possible, and attempts were made to set up interviews in advance of our visit.

Interviews were semi-structured in nature to allow for freer exploration and discussion around the various topics that were touched upon in conversation. The interviews utilised prompt questions which were used to steer the conversation, and touched upon the main topics of interest for research including: the general impacts of volcanic ashfall on the sector; actions taken in response to ashfall; ash clean-up and any associated problems; emergency management plans and interrelated power, water and access impacts on the sectors. However, conducting interviews through a translator meant that some questions needed to be phrased in a proactive manner, to maintain the focus of the interview and to avoid misinterpretations as a result of translation.

In general, the interviewee was asked to speak freely following a prompt question, and the translator would summarise the comments when they had finished. This allowed the researcher to have some level of continued exploration of some of the aspects mentioned in dialogue by the participant. But detailed explanations at the time were not deemed appropriate in the interview, in order to maintain the interest of the interviewee and to reduce the interview time.

Interviews were recorded and consent forms were signed by the interviewee(s) at the time of interview. A total of twenty recorded interviews were conducted during fieldwork in Ecuador, which varied in length from 25 to 105 minutes.

Of the intended participants, key staff at two of the hospitals contacted could not be interviewed; one because the appropriate person was away, and the other declined to be interviewed. It was not possible to set up interviews with water utility companies in Guayaquil and Riobamba owing to the tight time constraints of the trip.

Interviews were supplemented by the authors' own field observations, and by informal conversations with local people. A copy of the inventory of additional data collected during fieldwork can be found in Appendix 2. River water testing for turbidity, conductivity and pH readings were undertaken additionally in the Baños area, the results are presented in Appendix 3. Additionally a copy of newspaper articles from the May 2010 eruption can be found in Appendix 4.

1.4 Characteristics of the case study areas

This section provides some background information on Ecuador followed by a brief overview of the case study settlements visited for this study.

Mainland Ecuador has an area of approximately 256,000 km^2 and consists of three distinct regions: the coastal region, the central Andean region and the Amazon basin. The most recent census was carried out in November and December 2010; the population was measured at just over 14.3 million, an increase of 14% since the previous census in 2001.

Ecuador has substantial oil reserves and highly productive agricultural regions, and is a substantial exporter of bananas, other tropical fruit, sugar, flowers, cocoa and coffee, as well as petroleum, fish, shrimp, timber and gold. The GDP per capita is estimated at $USD 8,322.

1.4.1 Quito

Quito is located in the Guayllabamba river basin, in Pichincha province in the central Andean region of Ecuador (Figure 2). It is the second largest city in Ecuador, after Guayaquil, with a population of approximately 1.5 million. At 2850 m elevation, Quito is the second highest capital city in the world. The city sits on an extensive plateau that is part of the eastern slopes of Guagua Pichincha volcano. It is also adjacent to several other active volcanoes (Figure 2) and is vulnerable to ashfall. Both the 1999 eruption of Guagua Pichincha and the 2002 eruption of Reventador supplied millimetre thicknesses of ash to the city (Leonard et al., 2005). Suburbs to the south of Quito are also subject to lahar hazards from Cotopaxi volcano.

1.4.2 Baños

Named after the thermal springs located around the city, Baños de Agua Santa, commonly referred to as Baños, is located in Tungurahua province. It is the second-largest settlement, after Ambato, and has a population of approximately 16,000 (Lane et al., 2003). Baños is located at an altitude of 1800 m on the northern base of Volcán Tungurahua (5023 m), a stratovolcano located on the border between Tungurahua and Chimborazo provinces (Figure 2).

The economy of Baños is heavily dependent on tourism. Its features include a shrine dedicated to the Virgin of Baños, a mild climate, access to the Amazon basin, thermal springs and mountain scenery. In 1999, prior to the onset of volcanic unrest, 95% of economic activity in this community was dependent on tourism (Lane et al., 2003).

Prior to 1999, unrest at Tungurahua last threatened Baños between 1916 and 1918; at least one pyroclastic flow and several major lahars descended river valleys immediately to the east and west of the town (Hall et al., 1999).

While in Baños, the focus of our visit was on infrastructure impacts from ashfall, municipality volcanic hazard emergency strategies and volcano monitoring and warning systems. We also visited the nearby towns of Puyo, Ambato, Penipe, Quero and Cotaló to investigate the short and long-term impacts on infrastructure from volcanic activity since Tungurahua's reactivation in 1999.

1.4.3 Riobamba

San Pedro de Riobamba is the capital of the Chimborazo province in central Ecuador, located at the Chambo River valley. Riobamba (elevation 2754 m) is located 200 km south of Quito and 30 km southwest of Volcán Tungurahua (Figure 2). The city is a major regional transport hub and, along with Ambato, one of the major population centres in central Ecuador. Its population is approximately 125,000.

Riobamba's economy is heavily dependent on agricultural produce from surrounding rural areas. In recent years, direct road access from Riobamba to Baños has been heavily restricted following extensive lahar damage (Figure 1).

Several villages are dependent on this travel route for transporting goods and services elsewhere in the region. Plans to repair this road are indefinite.

Figure 1 Bridge on Rio Palitahua washed out by lahar from Volcán Tungurahua, near settlement of Penipe, on direct route between Riobamba and Baños.

1.4.4 Guayaquil

Guayaquil is the largest city in Ecuador with a population of 2.6 million in 2009. It is the capital of Guayas province and is the centre of Ecuador's business and manufacturing operations. The city sits on the western bank of the Guayas River, close to the Pacific Ocean and is Ecuador's main port (Figure 2). Guayaquil received ashfall from Volcán Tungurahua during the May 2010 eruption.

2.0 VOLCANIC HAZARDS IN ECUADOR

2.1 Overview of volcanic hazards in Ecuador

Ecuador lies to the east of a subduction zone, where the Pacific plate is being subducted beneath the South American plate. The subduction zone dips to the east underneath the South American continent. The tectonic setting has formed a terrain of approximately north-south trending mountain chains, collectively forming the South American Andes. In Ecuador these mountain chains include: the Cordillera Real, Cordillera Central, and Cordillera Occidental, which pass through the centre of Ecuador, from west to east respectively. Partial melting of the subducting plate has formed a broad chain of volcanoes within this mountainous zone (Figure 2). These volcanoes form the highest peaks in Ecuador.

There are 21 Holocene age (<0.01 ma) volcanoes listed for Ecuador on the Smithsonian Institute website (SI, 2010). The volcanoes of Ecuador vary in type and include: calderas, compound volcanoes and stratovolcanoes. The erupted magmas vary in composition from fluid basalts through to viscous rhyolites.

The tectonic setting of Ecuador renders it at risk from both earthquake and volcanic hazards. The volcanic hazards vary in accordance with the volcano type and magma composition. Large caldera-forming eruptions are highly explosive but infrequent. More frequent eruptions occur from stratovolcanoes with intermediate magma compositions that are associated with the following hazards: pyroclastic flows, explosions, ashfalls, lava flows and lahars.

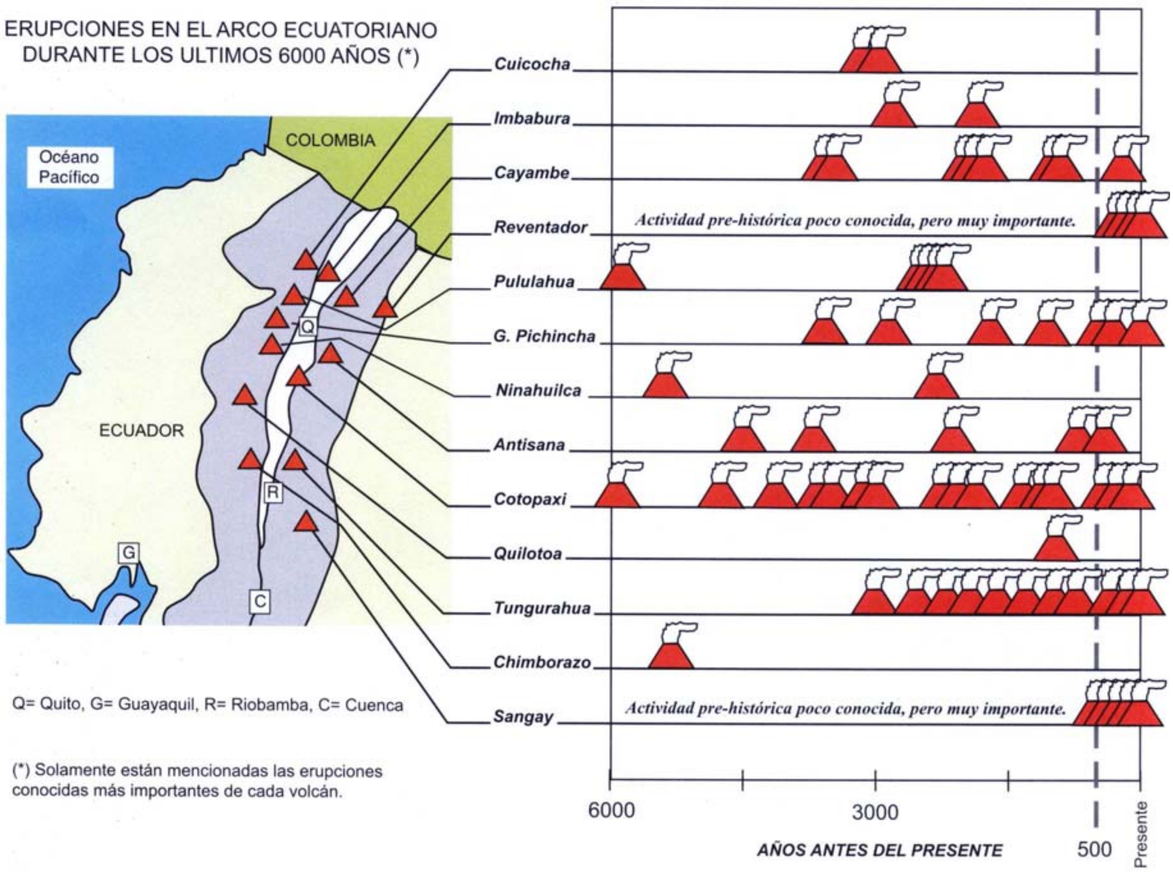

Figure 2 Map of Ecuador's volcanoes and chart of eruptive history (from Leonard et al. 2005 and IGEPN brochure).

2.2 Volcán Tungurahua: eruption history and volcanic hazards

Volcán Tungurahua is an andesitic-dacitic stratovolcano which rises to an altitude of 5023 m above sea level (SI, 2010). It is situated in the Cordillera Central of Ecuador; a mountain chain forming part of the Andes. Tungurahua lies approximately 140 km south of Quito, and around 8 km south-south-west of the city of Baños (Section 1.4.2). Many other small towns and villages occupy the slopes of the volcano and are at risk from volcanic activity.

Tungurahua is formed of three historic edifices: Tungurahua I, Tungurahua II and Tungurahua III. Tungurahua II was built after the collapse of Tungurahua I, but itself suffered a sector collapse and created a horseshoe-shaped crater, which is open to the west (SI, 2010). This feature is dated at 2955± 90 years old (Hall et al., 1999). Tungurahua III formed inside the Tungurahua II crater, undergoing two phases of construction: Phase I, 2300-1400 years ago, and Phase II, 1300 years ago until present. This construction of Tungurahua III has been characterised by andesitic lava flows, andesite and dacite pyroclastic flows and andesitic plugs (Hall et al., 1999).

All of the historical eruptions observed at Tungurahua have come from Tungurahua III; the youngest of the volcanic structures (SI, 2010). This youngest structure is referred to as Tungurahua or Volcán Tungurahua. Historic and recent activity of Tungurahua is shown in Table 2 and a map of Tungurahua's geology in Figure 3.

Volcán Tungurahua has been in a state of unrest since 1999, with many minor eruptions and also major eruptions in 2006, 2008 and 2010. The main styles of activity are Strombolian and Vulcanian. Volcanic hazards from the recent period of unrest have included: strong explosions, tephra falls, pyroclastic flows, lava flows and lahars, some of which have reached populated areas at the base of the volcano. These relatively frequent volcanic hazards directly threaten 25,000 people, as well as the Agoyan hydroelectric dam, which is located close to Baños (Hall et al., 1999).

Table 2 Summary of historic and recent activity of Volcán Tungurahua (sources: Hall et al. 1999; Barba et al., 2008; Lane et al., 2003; Samaniego et al., 2011; Arellano et al., 2008).

Date	Event
1641-1646	Historical reports of eruption exist, but there is a lack of reliable eyewitness accounts and stratigraphic confirmation.
1773-1781	Andesitic ashfall and dacitic pumice lapilli fall followed by large andesitic lava flow down NNW flank to Juive Grande; dammed Pastaza River for several days.
1797	Crater explosions coinciding with M8.3 earthquake that destroyed Riobamba.
1886-1888	Pyroclastic flows down W flank, particularly on NW where they partially buried 1773 lava flow, followed by lava flow down NW flank towards Cosua where it dammed the Chambo River.
1916-1918	Pyroclastic flows down NW and N flanks to Las Juntas and Vascún valley. Lava confined to crater.
October-November 1999	Onset of current cycle of eruptive activity. Elevated seismicity and SO_2 fluxes in September led to an eruption on 5 October. Evacuation of Baños ordered on 18 October. Townspeople returned on 5 January, clashed with authorities and won the right to stay in Baños at their own risk. Activity continued on cyclical basis with small to moderate explosive eruptions leading to ash emissions in August 2001, September 2002, October-November 2003 and May-July 2004.
July-August 2006	14-16 July: VEI 2 eruption. Pyroclastic flows towards NW, threatening Cosua and Juive Grande villages, and NNE, down upper Vascún valley. 16-17 August: VEI 3 eruption, largest in recent phase. Pyroclastic flows down NW and N flanks. During paroxysmal phase, there was a powerful lava fountain up to 1000 m above the crater, a 15 km high eruption column and pyroclastic flows down the N, NW, W and SW flanks with runout distances >8 km. Tephra fallout extended to the SW as far away as Guayaquil.
February 2008	Incandescent rocks and ashfall (Red Alert status).
May 2010	28 May: strong explosion with eruption column to 15 km altitude. Pyroclastic flows to NW, W and SW with runout 3 km down flanks. A lava lake formed in the crater. Ash plume extended to WSW as far as Guayaquil.

[1] Volcanic Explosivity Index (Newhall and Self, 1982)

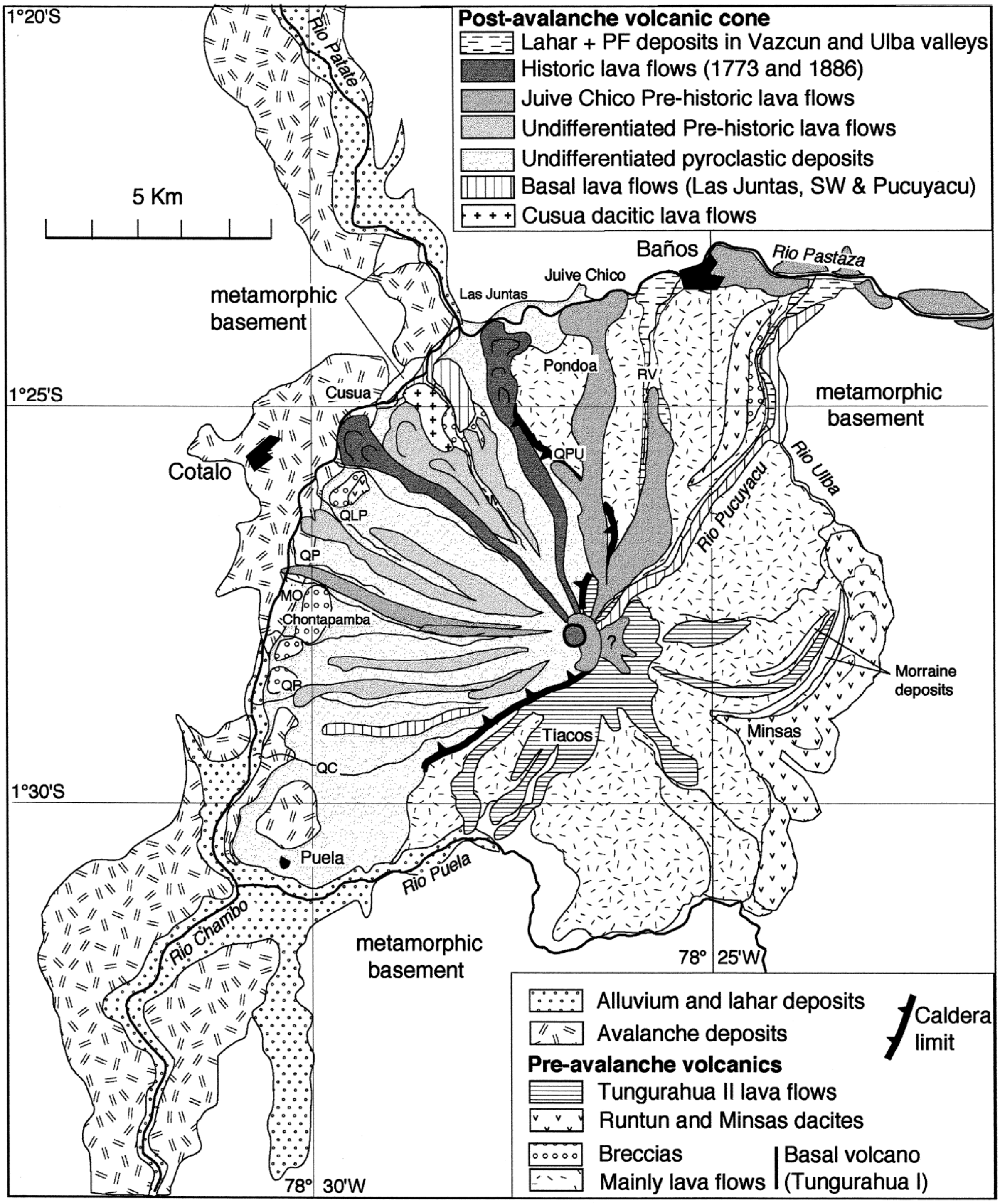

Figure 3 Geological map of Tungurahua, from Hall et al. (1999).

2.2.1 Volcanology of the 2006 Tungurahua eruption

Since the onset of volcanic unrest at Tungurahua in 1999, the eruptive activity was characterised from 2000-2005 by low to moderate explosiveness. These phases were strombolian with short duration explosions, plumes up to 7 km above the summit, and ash fallout on a regional scale (Samaniego et al., 2011). There were also periods of quiescence, such as between February to December 2005. However, in April 2006, IG-EPN monitoring detected deep seismic activity beneath the summit and an increase in SO_2 emissions. Increasing shallow seismic activity culminated in the 14 July (VEI 2) and 16-17 August (VEI 3) eruptions.

Activity on 14 July generated a 3-4 km high eruption column initially. The paroxysmal phase occurred between 19h40 on 14 July and 01h00 on 15 July, and gave rise to an eruption column over 20 km in height. At least 11 pyroclastic flows were generated, which descended the NW flank and the Vascún valley. Activity decreased on 15 July, but there were at least six small to moderate pyroclastic flows on 16 July (Barba et al., 2008).

On 16 August, activity increased again. The paroxysmal phase began at 00h15 on 17 August and involved a powerful lava fountain up to 1000 m above the crater, a 15 km high eruption column and the generation of major pyroclastic flows which descended 17 ravines on the north, northwest, west and southwest flanks. These flows travelled up to 8.5 km from the crater, and formed deltas in the valley of the Rio Chambo, which was blocked for several hours. The Puela and Pastaza rivers were also dammed by pyroclastic flows. The ash plume drifted to the west and deposited an ash and lapilli layer in the Interandean valley, with an uncompacted bulk volume estimated to be 40 x 10^6 m^3. Together with the pyroclastic flow volume of 10-15 x 10^6 m^3, this eruption is ranked as VEI 3, or approximately an order of magnitude greater than the 14 July eruption (Samaniego et al., 2011).

2.2.2 Volcanology of the 2010 Tungurahua eruption

In 2010, activity at Tungurahua increased and IG reported that on the 26th May there was a strong explosion from Volcán Tungurahua that sent an ash plume to 12km altitude, with ashfalls reported to the south and southwest. This explosion also generated pyroclastic flows that flowed north, northwest and west down the flanks of the volcano with run-out distances of <1 km.

On the 28th May another strong explosion occurred at Tungurahua that generated an ash plume to 15 km altitude. This was the strongest explosion of the 2010 eruption sequence. The plume travelled southwest and primarily affected the provinces of Bolivar, Los Rios and Guano (Figure 4).

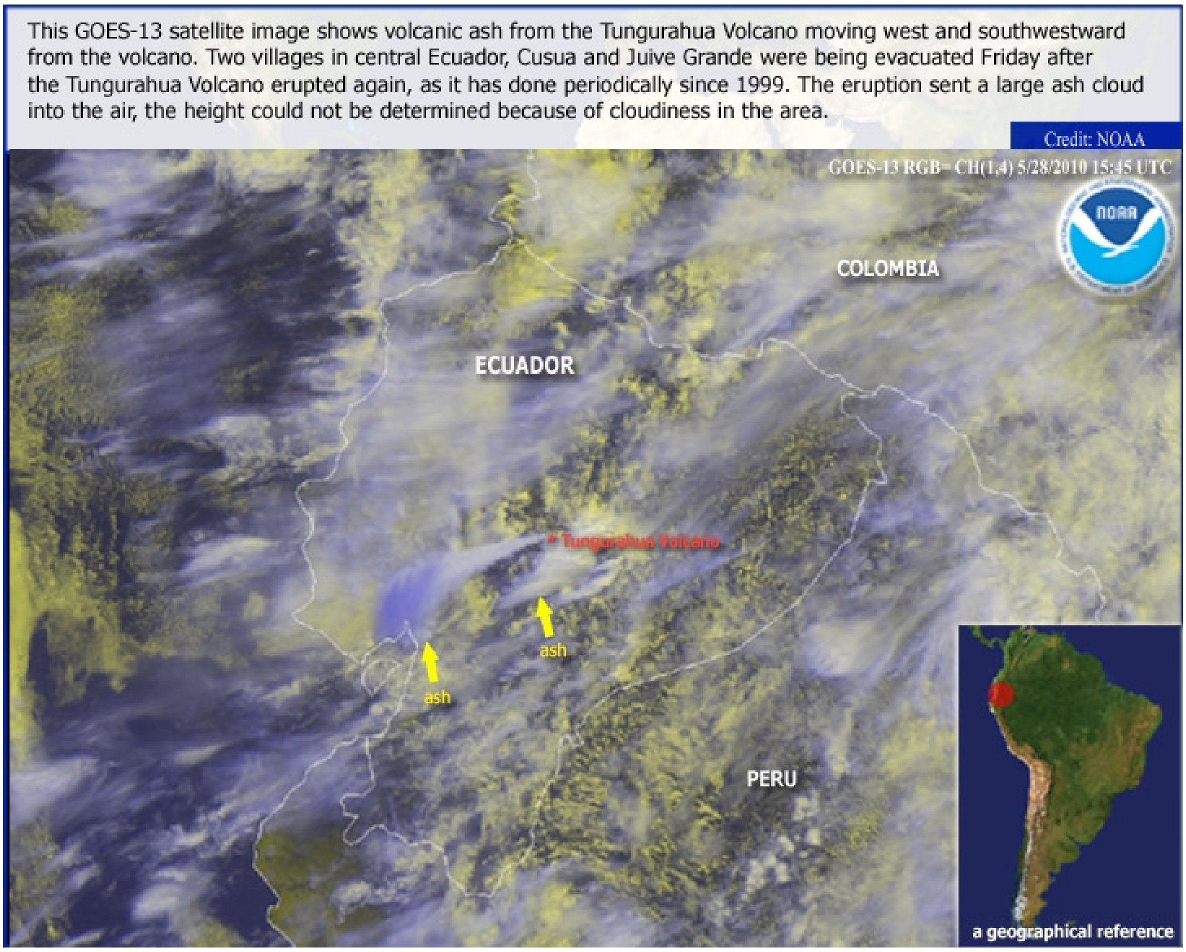

Figure 4 GOES-13 Satellite imagery of the eruption on 28th May 2010 (NOAA).

Thin (1-2 mm) ashfalls were received in Guayaquil, approximately 180 km southwest of Volcán Tungurahua. During this event, pyroclastic flows were generated to the northwest, west and southwest, with run-out distances of 3km down the flanks of the volcano. Pumice blocks also fell within 6-8km from the vent (IG, 2010). A map of the areas affected by the ash plume is reproduced as Figure 5, with the kind permission of the National Secretariat.

Activity continued on the 28-30th May, with 5-10 eruptions recorded per hour, and reports of “cannon shot” noises that caused windows to vibrate in the local area. Steam and ash plumes reaching <10km altitude, with ashfall reported in areas within around 8km to the northwest, west and southwest continued, and “cannon shot” noises and bombs ejected within 2km of the summit, continued to characterise the activity of this eruption into the month of June (IG, 2010). On 2nd June another pyroclastic flow occurred to the northwest, and on 5-7th June ashfall was reported at a greater distance of 23km from the vent (IG, 2010).

Ashfalls resulting from this eruptive period were found to be coarse grained in Cotaló, proximal to the volcano, reducing in grain size to a very fine powder in Guayaquil. At the time of writing there was no data available to quantify the ash grain size or composition.

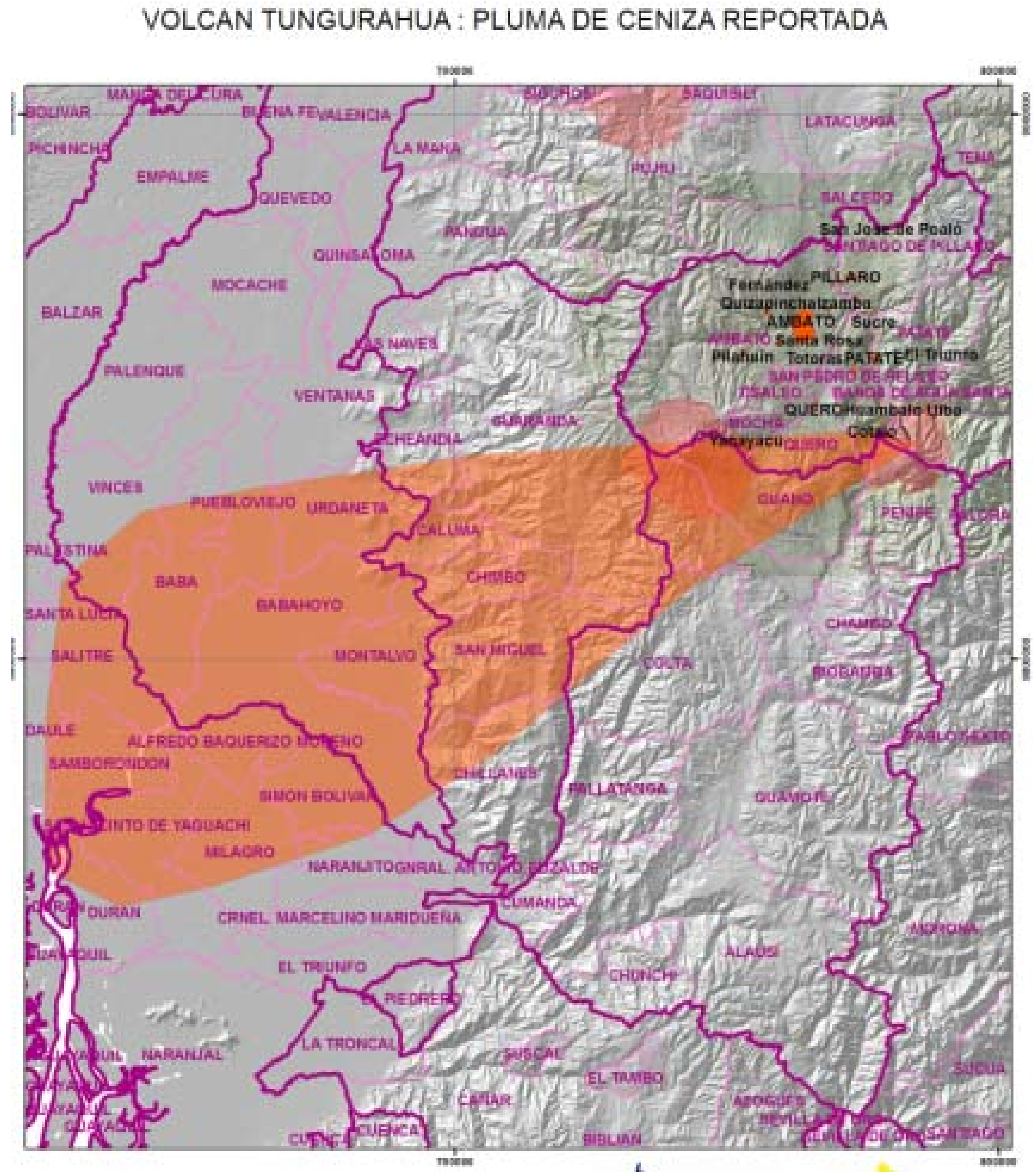

Figure **Error! No text of specified style in document.**5 Ash plume from May 28 2010 eruption of Tungurahua (reproduced with the permission of the National Secretariat).

During the unrest in May 2010 IG produced four hazard scenarios for the National Secretariat which are shown here as Figure 6 to Figure 9 (reproduced with permission from the National Secretariat).

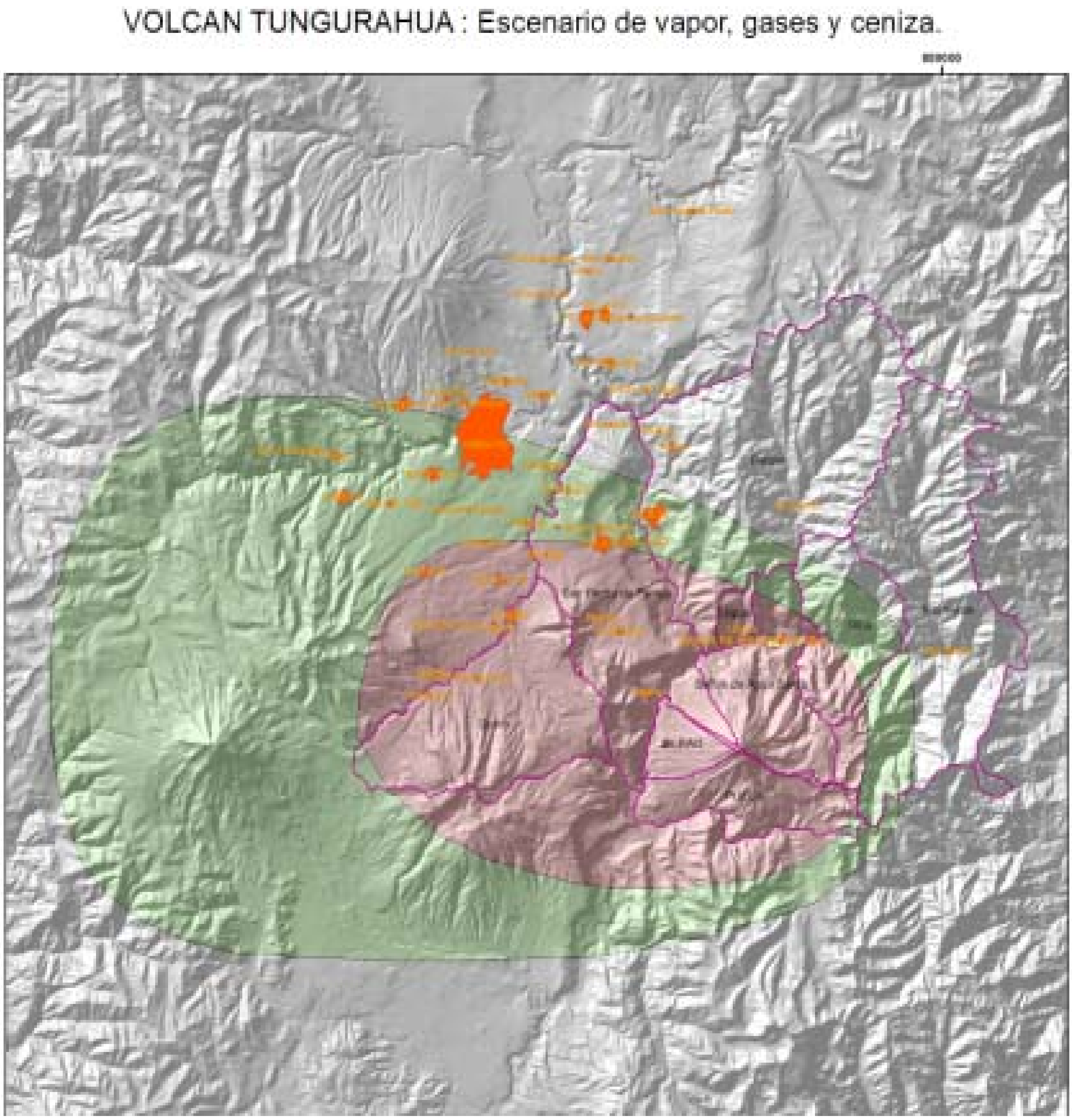

Figure 6 Hazard scenarios produced by IG during volcanic unrest at Volcán Tungurahua in May 2010. Scenario: pyroclastic flows.

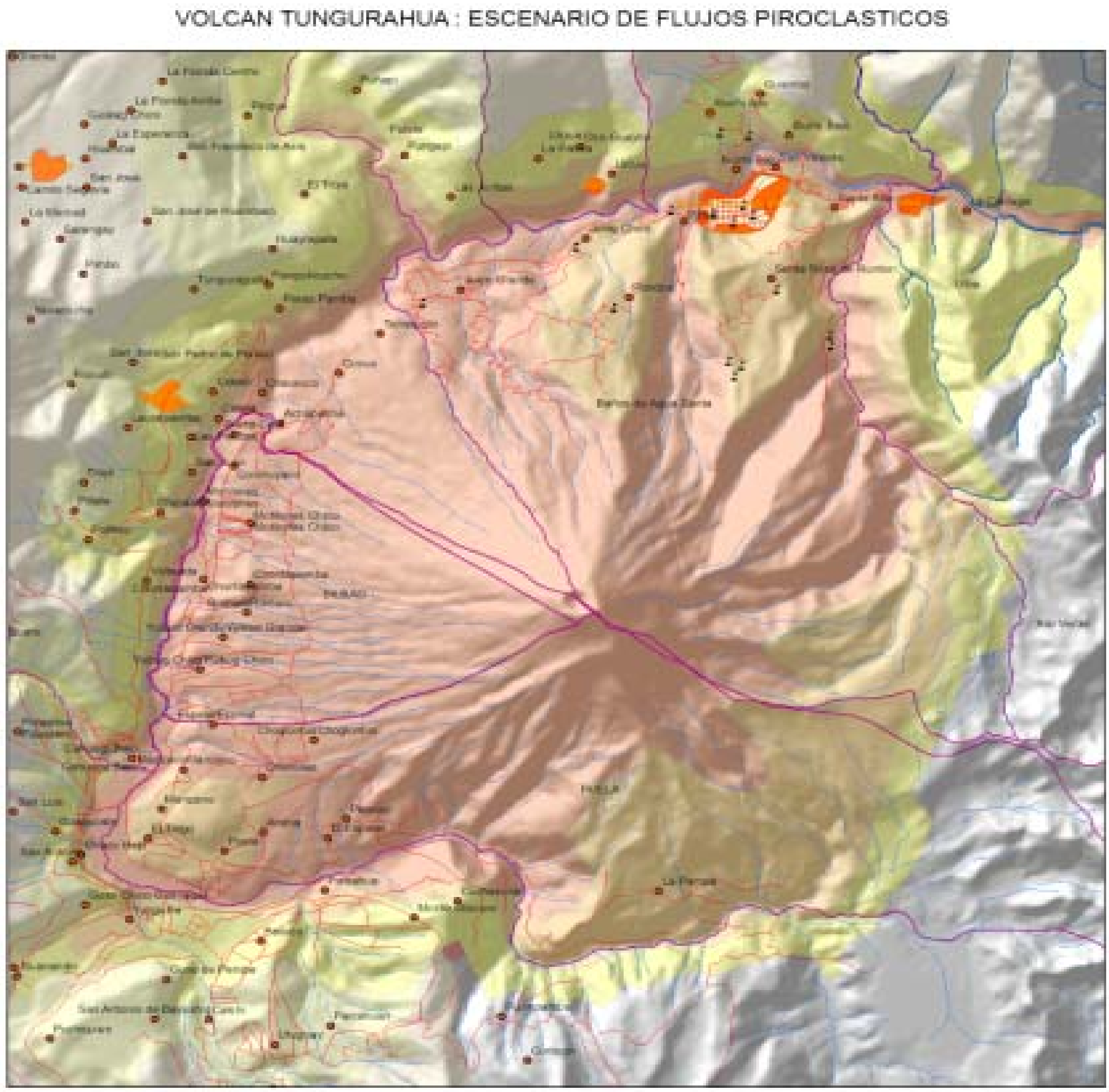

Figure 7 Hazard scenarios produced by IG during volcanic unrest at Volcán Tungurahua in May 2010. Scenario: gas and ash eruptions.

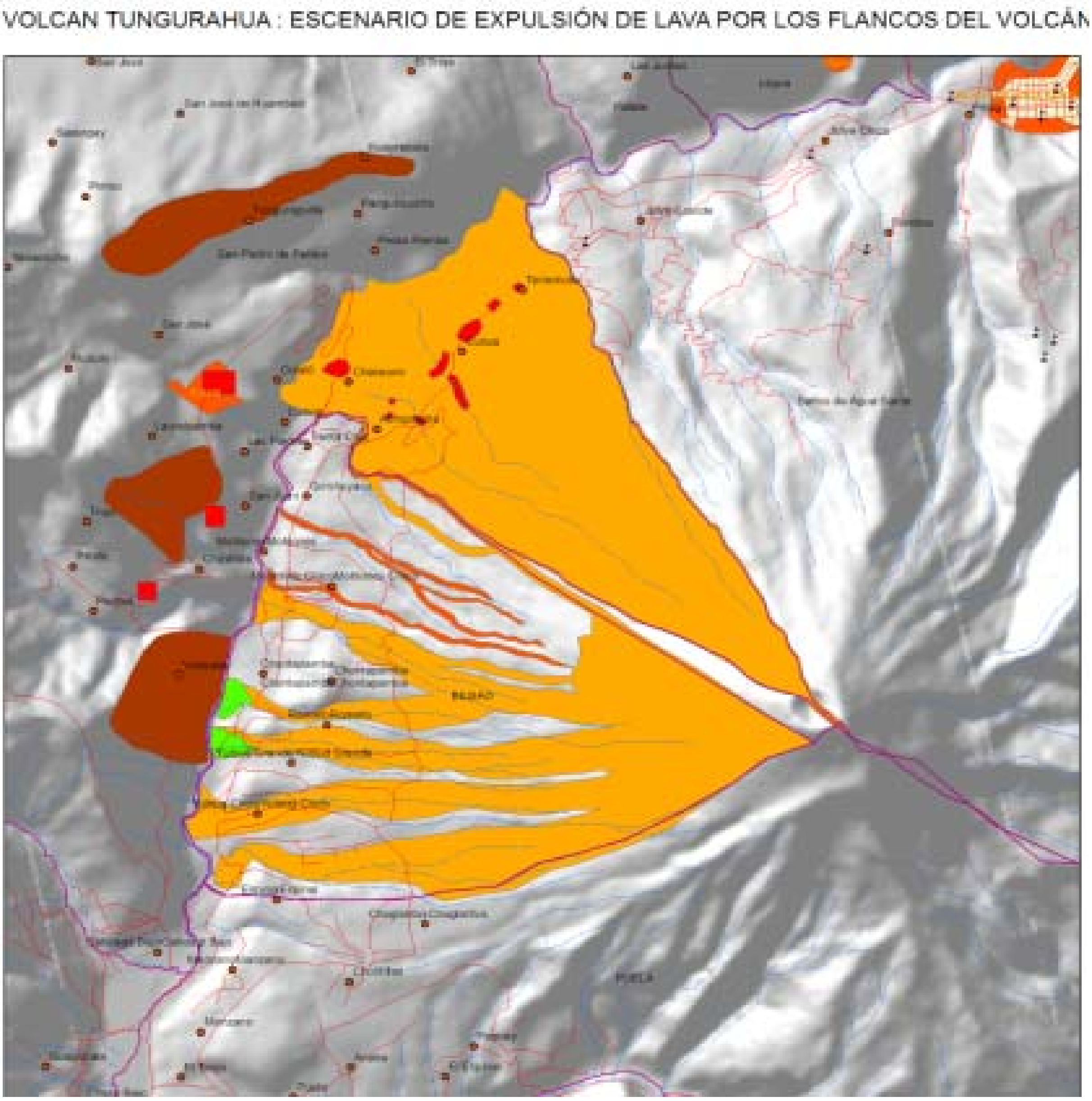

Figure 8 Hazard scenarios produced by IG during volcanic unrest at Volcán Tungurahua in May 2010. Scenario: Lava lake overflow.

VOLCAN TUNGURAHUA : ESCENARIO DE PERDIDA DE ENERGIA

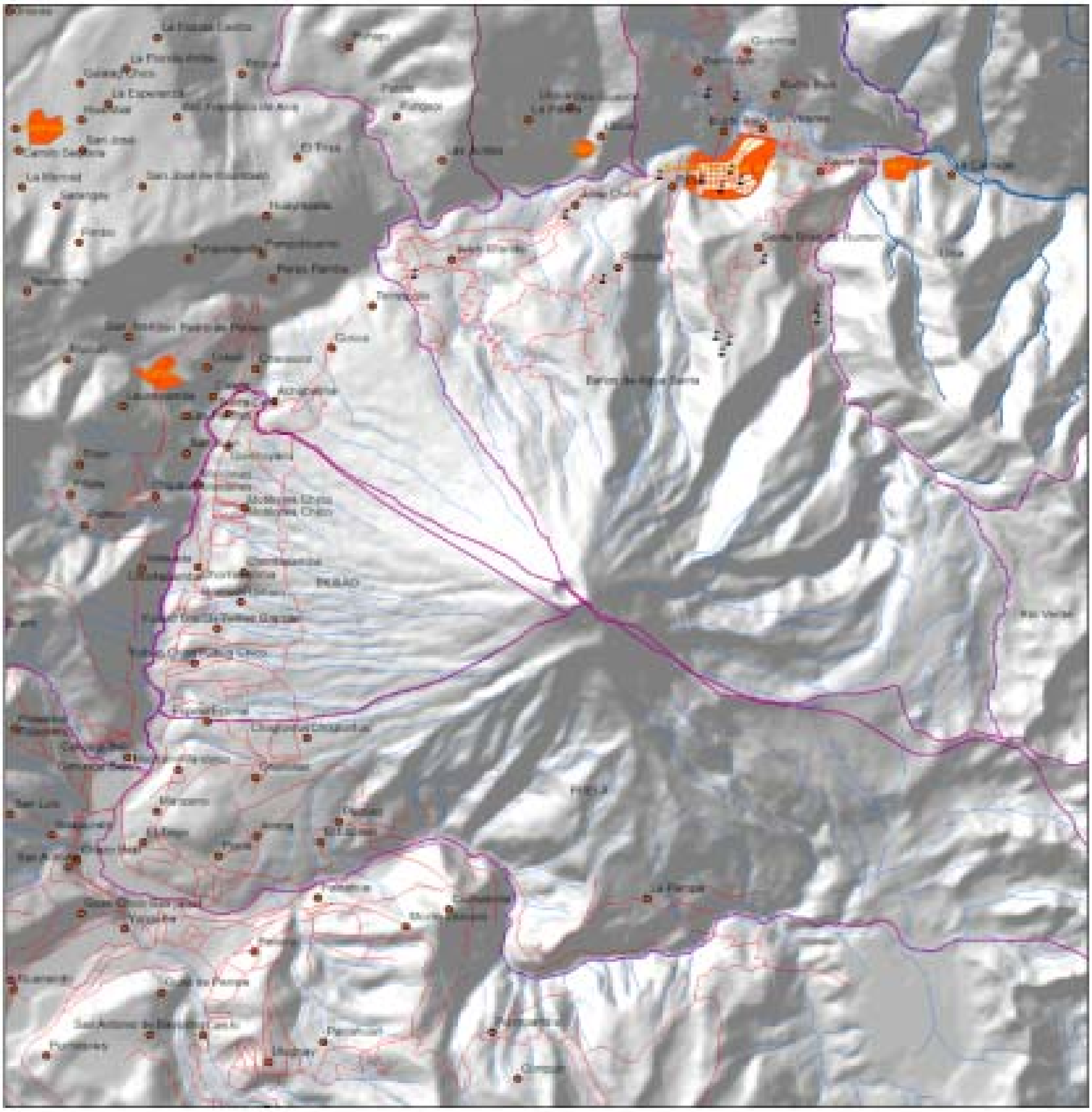

Figure 9 Hazard scenarios produced by IG during volcanic unrest at Volcán Tungurahua in May 2010. Scenario: Decrease in activity.

During this period of unrest, some of the small villages were evacuated ahead of the pyroclastic flows on the 28th May 2010. Five hundred families in five communities close to the volcano were reported to have been evacuated by the authorities, with an unknown number of people self-evacuating from the area (Silva, 2010). However, in the city of Baños, an evacuation order was not given by the local government (see Section 0 for more details about the history of evacuation in Baños). Despite the lack of official evacuation order in Baños, the National Secretariat told us that many people from the nearby area, including Baños, auto-evacuated. Schools in Baños were also closed so that children could remain with their families in case of an evacuation order.

Activity following the 28th May 2010 eruption has also included lahars, which affected the Penipe-Baños road between 28th May and 14th June 2010 and caused the road to close. Mudflows have also occurred in the area between 4th and 6th September 2010. This road was inaccessible at the time of fieldwork.

2.3 Volcano monitoring and warnings

The monitoring of volcanoes in Ecuador is carried out by Instituto Geofisico Escuela Polytechnica Nacional Apartado (IGEPN, or IG), which is based in Quito. The IG also runs the Tungurahua Observatory, which is located in Guadeloupe, 14km north of Volcán Tungurahua. Seventeen volcanoes are actively monitored in Ecuador. Different monitoring networks are installed at each volcano; elements include seismic stations, ground deformation and pressure sensors, thermal, geochemical and visual data.

The Tungurahua Observatory provides daily reports on activity at Volcán Tungurahua and operations at the Observatory. In addition, they also produce ‘special reports’, which include data from the monitoring network (seismic stations, GPS and gas emission data).

The monitoring equipment and data collection from the Tungurahua Observatory includes: seismometers, tiltmeters, COSPEC and DOAS monitoring, two lahar detection stations, thermal imagery, ash collection and chemical analyses (WOVO, 2005). This monitoring is supplemented by observations from the Observatory, and from “vigìas”, who are trained local volcano watchers with radio communications to the Observatory.

When unrest manifests at the volcano, IG inform the National Secretariat of Risk Management (otherwise known as the “National Secretariat”) and provide hazard scenarios for the likely progression of activity. The National Secretariat makes contingency plans, based on the likely hazard scenarios provided by IG, which are then given to the local government.

It is the decision of the local government to assign the alert level, and to give evacuation orders if necessary.

At the time of writing, the alert level system and contingency plans were under review by the National Secretariat, and new procedures were being developed. There are plans to: develop the contingency plans to better fit with the hazard scenarios provided by IG and to provide information on what actions people should take in each scenario; alter the alert level system, which currently varies between municipalities; and train local government officials to be able to lead in emergencies. The plans are intended to be complete by the end of 2010.

3.0 INFRASTRUCTURE IMPACTS AND RESPONSES TO RECENT ASHFALL

Infrastructure impacts were investigated in Guayaquil, and also in several centres in the Tungurahua area (Figure 10). Additionally, meetings were carried out informally with IG staff, and informal conversations were opportunistically undertaken with local people when visiting the affected area.

Time constraints allowed focus on a few main topics of interest, to unravel the complexities of impacts across these areas. Unfortunately it was difficult to arrange interviews within the time frame, and little information was gained on water, wastewater, and transportation and communication infrastructure directly. However other interviews provided insights into the impacts on these sectors, particularly since the focus of the trip was to look at both direct and indirect effects of ashfall on critical infrastructure. Indirect effects included how access, power, water and communications affected the operation of critical facilities.

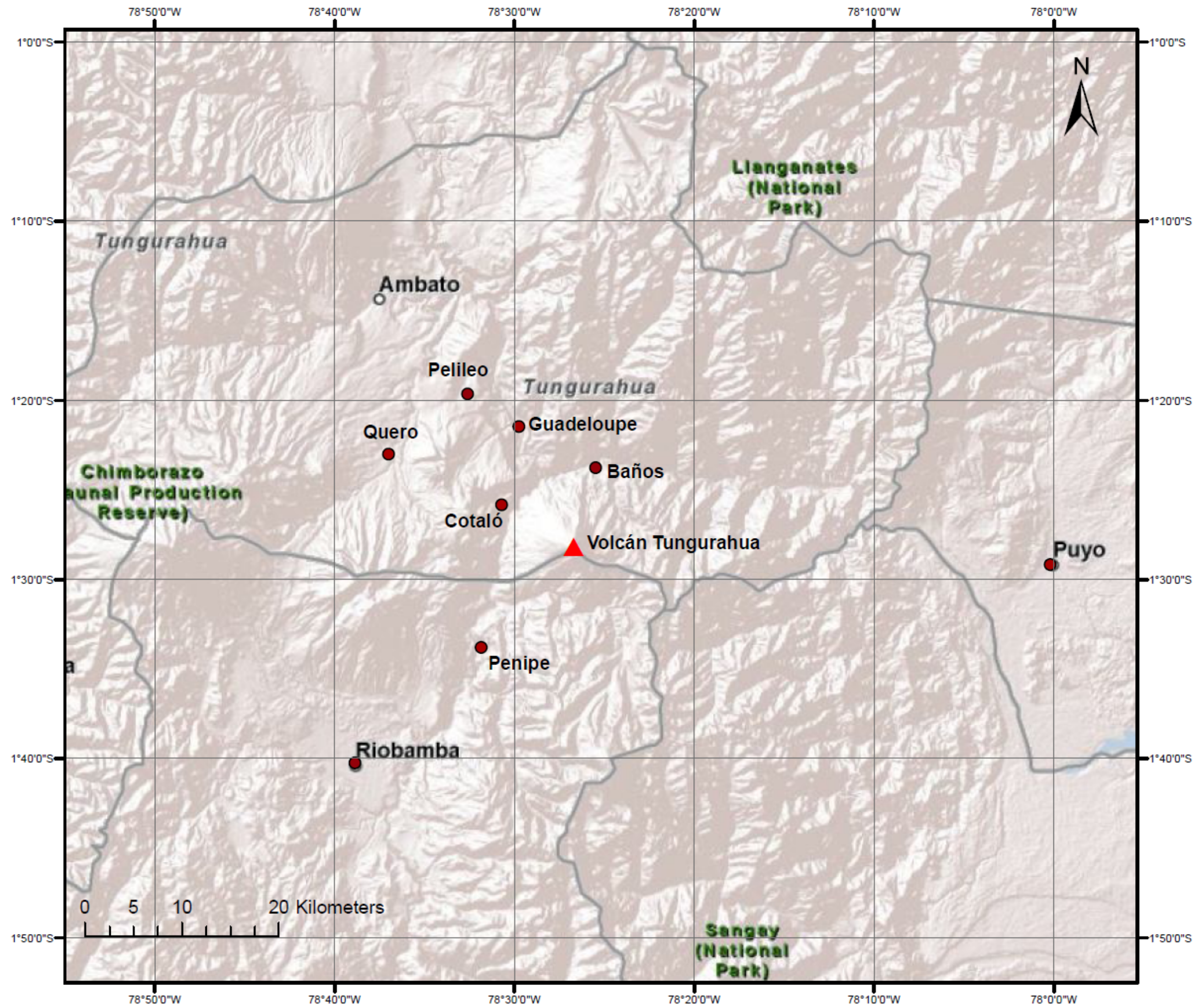

Figure 10 Map of the towns visited in the Tungurahua area to investigate the impacts of volcanic ash.

Impacts are discussed in the following sections, by sector.

3.1 Electricity supply

3.1.1 Organisational and operational structure of the electrical network in Ecuador

The company CELEC EP (La Empresa Publica Estrategica Corporacion Electrica Del Ecuador) is responsible for operating the nation's electricity transmission network. Formed on January 14 2010, CELEC EP is the single entity that oversees several businesses within the nation's wholesale electricity market. These businesses manage different facets of the energy supply process such as generation and distribution.

The total electricity demand for Ecuador is approximately 2800 MW. The city of Guayaquil is the nation's largest energy demander consuming roughly 700 MW, while Quito follows closely behind with a demand of about 600 MW. A centralized, double-circuit power transmission network forms a 'ring' that is capable of generating and transmitting a maximum of 4000 MW to provide consumers with a constant and reliable power supply (Figure 11). Ecuador's electricity transmission network is comprised of 32 substations connected by some 3,000km of transmission lines operating at either 230 kV or 138 kV (Transelectric, 2011). Electricity is generated through the transformation of energy from fuel combustion, hydro systems, steam, natural gas and wind (only on the Galapagos).

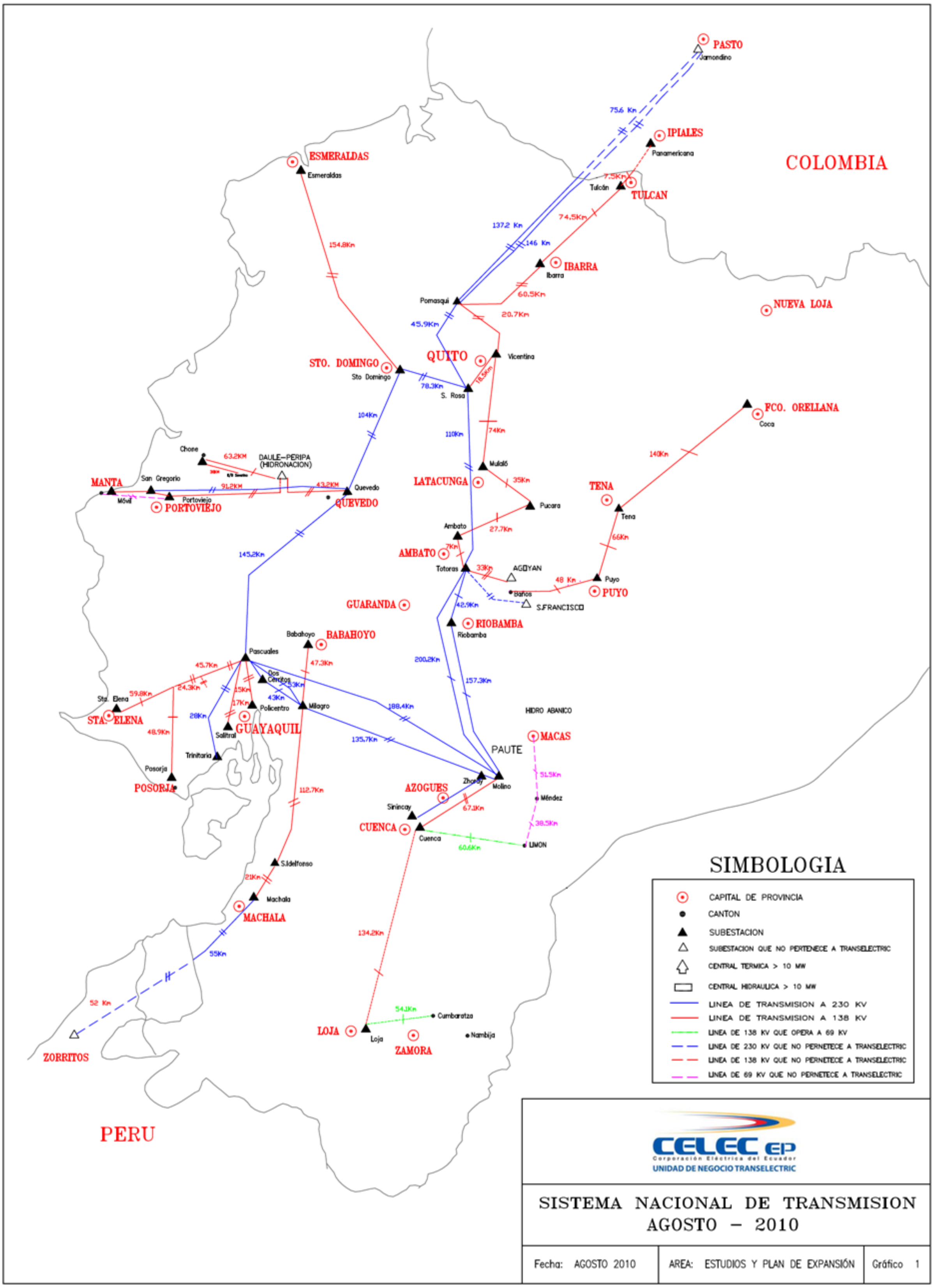

Figure 11 Map illustrating the Ecuadorian transmission network. Image courtesy of CELEC EP.

3.1.2 Generation sites

The Agoyan hydroelectric dam, situated on the Pastaza River, is located five kilometres east of the city of Baños. This dam generates 156MW and each generator produces a voltage of 33kV. This voltage is then stepped up to 138kV for integration into the national grid. The dam and its reservoir are the second most important in Ecuador (Hall et al., 1999).

Over the last 11 years of intermittent volcanic activity from Tungurahua, very little ash has fallen at the dam site. This is mainly due to the predominant wind direction of the region which tends to carry ash south and west of the volcano (a scientist[1]). On the few occasions when ash has fallen at Agoyan, the dam has operated as normal unless the local municipality deems the community risk too great; as occurred during August 2006 and October 1999 when large volumes of ash fall threatened the security of Baños, which resulted in the closure of local utilities. The dam is equipped with a regularly updated contingency plan covering major disasters such as a large volcanic eruption from Volcán Tungurahua. Daily communication is maintained between dam operators and the Observatorio Volcánico Tungurahua (Tungurahua Volcano Observatory) to ensure preparedness for volcanic events.

The lahar hazard from Tungurahua is more threatening to the Agoyan hydroelectric project than direct ashfall (an Agoyan Dam Operator). Intake mechanisms such as wicket gates, turbine covers and blades are particularly at risk of abrasion from ash-laden water. Severe pitting of the metallic components (Figure 12) has accelerated their degradation; Agoyan has had to replace four turbines in the last 21 years.

To reduce the impacts from the intake of highly turbid water, Agoyan is specially designed to cope with high levels of sediment. A floodgate system has been devised so that the intake flow can be diverted away from generation components and directly flushed out into the river via flood gates (Figure 12). In the event of heavy rain, when there is an increased risk of ash-laden floodwaters and lahars being generated, the dam has systems in place to monitor water levels and turbidity to trigger the protective bypass system.

[1] Interviewees have been anonymised, and generalised terms relating to their employment has been used to indicate where interviews have been referenced, in accordance with ethical guidelines

Figure 12 Above: a severely pitted turbine that has been removed from service. Below: the Agoyan Dam and its orange floodgates.

3.1.3 Substations

Ashfall from the May 28 2010 eruption instigated no faults on Ecuador's transmission network and created only minor cleaning issues. The city of Guayaquil received 1-2 mm of fine-grained ash during this eruption, a rare event for the city (Figure 13). The ash fell during dry conditions and no instances of flashover (the unintended discharge of electrical current across insulators) were reported. This coincides with earlier work which suggests that dry volcanic ash is non-conducting and will not cause immediate problems (e.g. flashover) to high voltage transmission equipment (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981, Matsuoka et al., 1995). The risk of flashover is believed to be greater in light wet weather conditions (dew, fog, drizzle or light rain) (Wilson et al., 2009).

Immediately following this ashfall, crews were dispatched to survey substations. Substations identified as most affected were cleaned to prevent ash-induced failure of high voltage equipment.

The Guayaquil substation (Pasquales) is of critical importance to the continuity of the power supply to the city, and it required the most attention from line maintenance and cleaning crews. During the cleaning process, all personnel were required to wear a mask and goggles. To avoid interruption to supply, the substation remained energised while insulated batons (rated for 230 kV) were fitted with brush heads and rags as the cleaning crew manually cleaned the surfaces of all substation equipment except for transformers (e.g. switches, bus bars, conductors, etc.). 'OMYA' brand ceramic cleaning detergents were used to aid in the primary cleaning stage (applied by rag or brush) before high-pressure power washers were brought in to thoroughly rinse away any remaining ash. To avoid permanent damage to the power transformers, each of the three transformer banks at the Pasquales substation had to be taken offline individually while these sections of the yard were cleaned. Only eight hours of total de-energized time was allowed by CELEC EP for this procedure. The substation was re-energized once drying of substation equipment (following high pressure washing) was complete. While remobilization of the ash was an inconvenience to substation workers for about a month following the initial ashfall, no further cleaning of equipment was required.

Disconnect switch contacts were especially difficult to clean and required scrubbing with a rough sponge to remove the contact grease in which the ash became embedded. This protective grease was then reapplied (Figure 13).

Immediately following the May 28 2010 eruption, a separate live-line cleaning crew was dispatched to Babahoyo substation, located approximately 125 km WSW of Tungurahua in Los Rios province (Figure 5). This station is equipped with only one three-phase transformer that feeds several distribution circuits. Special care and attention was given to this small station, as transmission failure here would have likely caused cascading failure elsewhere on the grid.

While the May 2010 eruptions of Volcán Tungurahua caused only minor and short-term problems for substations, the August 2006 eruptions caused more problems (a CELEC EP Linesman.). Substations affected by ashfall from these events (Riobamba, Totoras, Pucara and Babahoyo) required extensive controlled-outage cleaning. CELEC EP personnel noted that fine-grained ash was the most difficult to clean, especially when it became wet and cemented to the surfaces of substation gear.

Despite significant ashfalls to substations during Tungurahua's eleven-year period of recent activity, no issues or concerns have been raised about the reduction of step-touch potentials in substation gravel contaminated with volcanic ash, nor have any issues of corrosion or abrasion been reported.

Figure 13 Above: 138 kV transformer bushing coated in 1-2 mm of fine-grained ash at a Guayaquil substation. Below: a contaminated disconnect switch. (Photos Courtesy of Transelectric, Ecuador).

3.1.4 Transmission and distribution equipment

Following the May 28 2010 eruption of Volcán Tungurahua, transmission conductors (lines), insulators and towers were not cleaned because previous experience with ashfall suggested that minor quantities of ash would unlikely cause problems and that wind and rain action would provide sufficient cleaning of transmission equipment. This conforms to advice provided by Wilson et al., (2009) whereby small volumes (<5 mm) of dry volcanic ash will have a low probability of causing failure (flashover) across the insulator.

In general, Ecuadorian transmission equipment is more susceptible to flashover from other contaminants such as industrial emissions, salt spray, fertilisers and mould than from volcanic ash (a CELEC EP substation supervisor). However the investigations of Sarkinen and Wiitala (1980) have highlighted the extremely high potential of volcanic ash to cause flashover on high voltage transmission equipment due to the large amounts of attached soluble salts which become conductive when dissolved by a source of moisture (rain). The decision to not clean transmission conductors, insulators and towers should therefore be revised to avoid flashover on high voltage insulators which can cause cascading failure elsewhere on the power system.

When asked for their views on the vulnerability of different configurations of insulators, CELEC EP staff thought that vertical configurations would be more susceptible to flashover due to the higher surface area for ash to adhere to (a CELEC EP Linesman; a CELEC EP substation supervisor). This is interesting to note as other anecdotal evidence suggests the contrary, whereby horizontally strung insulators allow ash to adhere to the underside of insulator sheds more readily and are therefore more likely to bridge the distance between electrodes (conducting elements). While the majority of high voltage insulators in Ecuador are made from red porcelain, glass insulators with larger creepage distances (distance between the conducting elements on an insulator or string of insulators) are recommended for heavily polluted regions, and those at risk of ashfall. Glass is also preferential because it is easier to tell over the red porcelain when the insulators are contaminated and require cleaning from lines crews (a CELEC EP Linesman).

Transmission equipment located on the northern flank of the volcano has had to be re-routed due to lahar hazards (Transelectric officials). Lahars in 2006 came within metres of a 138 kV transmission tower, initiating a plan by CELEC EP to relocate the tower to avoid future lahar-induced interruption to the high voltage supply around the volcano (Figure 14).

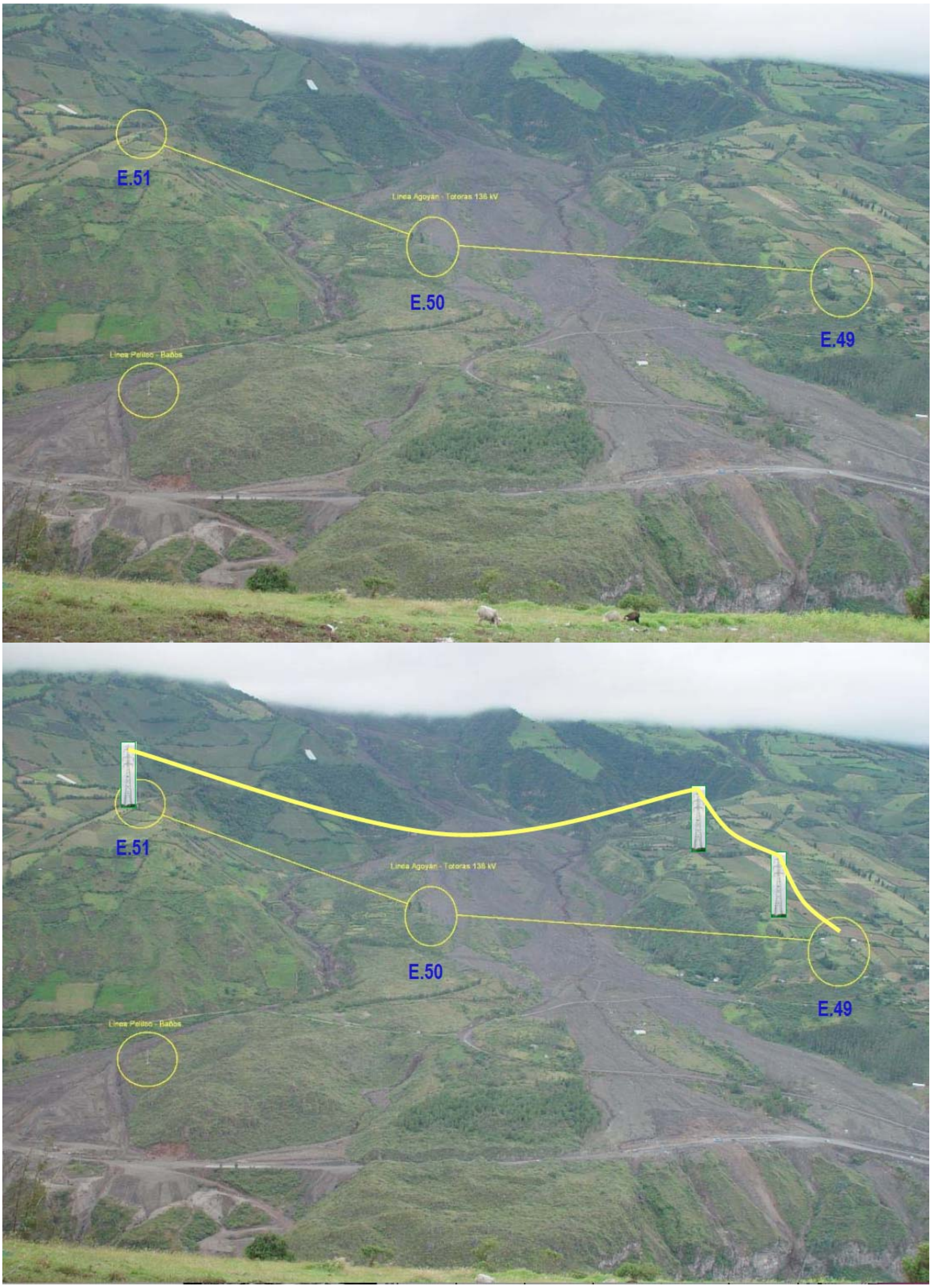

Figure 14 Above: 138 kV transmission tower (E50) situated in a 2006 lahar path. Below: Proposed re-design of the 138 kV transmission circuit showing relocation of towers and conductors (lines) to avoid lahars (Photo’s courtesy of Transelectric, Ecuador).

3.1.5 Summary of impacts and adaptations to electrical supply

The Agoyan dam is vulnerable to lahar hazards, and turbine blades suffer increased abrasion as a result of the water turbidity. Risks of lahars are higher in the rainy season; dam operators monitor turbidity of the water and floodgates have been designed to bypass turbid water away from the generation equipment to prevent damage. While no major failures have occurred at Agoyan the dam stopped its operations due to the risk posed by large eruptions at Volcán Tungurahua in 1999 and 2006. The risk is managed with daily communication between the Agoyan dam and TVO. Transmission towers on the northern flanks of the volcano are also vulnerable to lahar hazards and CELEC EP has identified an alternative site for the towers to mitigate the risk.

Overall the Ecuadorian electricity transmission network performed very well during the May 2010 ashfall. Because the ash 1) fell in small amounts (1-2 mm in Guayaquil) and 2) fell in a dry state during dry atmospheric conditions, the ash was non-conducting (Nellis and Hendrix, 1980; Sarkinen and Wiitala, 1981) and therefore posed a low risk of causing flashover (Wilson et al., 2009). Had it been raining or very humid conditions at the time of the event, the risk of flashover would have increased and more immediate actions would have been necessary (e.g. de-energisation of critical circuits for controlled outage cleaning or immediate ‘hot’ (energised) cleaning of both contaminated substations and transmission equipment). In general, flashover events are more common from other contaminants in Ecuador, such as salt spray, industrial contaminants and guano. Pre-existing knowledge of the risks posed by these alternative contaminants has influenced the strategies taken by Ecuadorian electricity personnel to mitigate adverse impacts to the power system from volcanic ash fall contamination.

Our findings highlight the heightened vulnerability of substation equipment (e.g. transformer insulation (bushings) and switchgear) over transmission hardware (conductors, insulators, towers) during a light ash fall event such as occurred in May 2010. Extra care should therefore be given to these components to ensure a constant and reliable supply of electricity. Effective cleaning methods have been developed by CELEC EP in response to ashfalls in order to prevent damage. CELEC EP identified vulnerable substations and these were assessed and cleaned as a precaution. Transmission equipment was not cleaned following the light ashfalls in May 2010, as the ash was considered too thin to pose a risk of failure and it was considered that rain and wind action would clean the equipment sufficiently. The unfailing provision of electricity to affected areas during the May 2010 eruption was largely due to sensible decisions made by Ecuadorian electricity managers but the performance of the system should be brought to the attention of international power suppliers as an example of resiliency during a minor volcanic ash fall.

Larger ashfalls in 2006 prompted controlled outage cleaning to a few substations in the affected area. Lessons learned from adverse impacts during this and other regional volcanic eruptions (e.g. Reventador 2002) have helped electricity managers prepare for and make sound assessments during volcanic ashfall events, such as in May 2010. However, large scale events (e.g. 2006) require different and more complex mitigation strategies.

3.2 Water supplies

Investigations of impacts on water supplies were not a focus of this field visit as within the tight time frame available only one interview was unable to be arranged. Good information on the range of adaptive measures adopted by the water supply agency EMAAP in Quito to mitigate against the frequent ashfalls experienced by the city is provided by Leonard et a. (2005).

3.2.1 Guayaquil

We interviewed an environmental monitoring officer at the Municipality of Guayaquil about the impacts of the ashfall on the city's lifelines. The city received approximately 1 mm ashfall, with lesser quantities being received towards the south of the city. The ashfall lasted around two hours, and was 'very fine, dry and dark grey in colour'. The officer made the point that as Guayaquil already has a high baseline of environmental quality problems (such as air and water quality) any additional impacts from the ashfall could not be differentiated from this baseline. The municipal water supply implemented short-term service outages (up to one day per sector) to allow filters to be cleaned or changed as necessary. The municipal cleanup was reportedly a minor operation mostly performed by residents using brooms (known as 'mingas'). No water shortages were reported as a result.

3.2.2 General vulnerability of water supplies in Ecuador

According to the National Secretariat, of all of the lifeline services in Ecuador, water supplies are generally the most affected by volcanic ashfalls. However further details of the way in which they are affected by ashfalls is not known. However, a supporting insight was provided by PAHO staff, who told us that there is a new health ministry initiative to protect drinking water from ashfall, and to provide filters in affected areas.

Hospitals interviewed during this study reported that their water supplies were unaffected during the 2010 eruption. However local communities suffered digestive system problems from drinking contaminated water and eating contaminated food. In response to an open question about the consequences of ashfalls in the Penipe area, a hospital manager told us:

"*…we have a greater incidence of diarrhoeal problems and skins problems, dermatitis, allergies … parasitic infections, parasitic diseases that are caused because, well because the water is contaminated, and also because people are ingesting foods that have ash in them. I'm talking about fruits and vegetables, and pretty much everything that is harvested here in the region*."

Local volcano watcher (vigìa) recommended that home water supplies be covered to protect them from contamination.

Measurements made of stream water quality in the Tungurahua area are included in Appendix 3.

3.3 Healthcare facilities and services

This section gives an overview of: the structure of the healthcare system in Ecuador; the reports and observations gained from visiting healthcare centres in Ecuador; and a summary of the types of socio-physical system adaptations noted during fieldwork, drawn from interviews and observations. This report provides the preliminary findings of this study. Further analysis of the interviews and data is ongoing.

3.3.1 Structure of the healthcare system in Ecuador

The health sector is comprised of public and private institutions as well as non-profit and for-profit institutions. The public sector tends to the needs of approximately 59% of the population, private for-profit institutes cover 10% of the population, armed forces and police tend to1% of the population, and 30% of the population do not receive any formal medical care (PAHO, 1998).

The healthcare system is decentralised in Ecuador, comprising centres of variable sizes with a chain of progression of services, leading up to regional centres of health. The Ministry of Health’s decentralisation model is based on creating small service networks with decentralised technical capabilities, each with defined geographic and population catchments (PAHO, 1998). Hospitals are the largest centres with the most services, followed by centres of health, and then sub centres of health, which are for primary healthcare services. During emergencies, mobile groups are formed of medical professionals, known as “brigades”. These groups attend the “Albergue’s” (shelters) in the affected area during times of eruption, and are typically formed of: assistant nurses, nurses, doctors (GP’s) and psychologists.

In 2001 the annual spend on public health as a proportion of GDP was 4% (PAHO, 2001). However, according to a PAHO official interviewed at the time of fieldwork, the budget for health has increased by 300% with the new government and constitution in place since 2008.

3.3.2 Impacts on the healthcare system

The impacts of volcanic ashfall on healthcare systems and services were investigated during the fieldwork in Ecuador, in both Guayaquil and in the Tungurahua area. The data collection comprised interviews at several centres including in: Guayaquil, Puyo, Baños, Riobamba, Quero, Pelileo and Penipe. These sites are a various distances from Volcán Tungurahua and located at different compass orientations; from the east, through to the north, northeast and southwest (See Figure 10).

Because the private healthcare sector serves a small percentage of the population, the focus was placed on public sector health centres, to gain a fuller understanding of the problems associated with ashfall across a greater proportion of the population. Two private centres and six public health centres were included in the interview pool, plus an interview with the Pan American Health Organisation (PAHO).

3.3.3 Overview

There were varied reports of the effects of volcanic ashfall on several healthcare systems in the Tungurahua volcanic area, and one hospital in Guayaquil. Overall, health centres further from the volcano reported few problems with ashfall in terms of: ash ingress into buildings, and demand for, and changes to, the healthcare services provided. However prolonged working hours were required by staff as health centres increased their operating hours. Additionally, few protective actions were deemed necessary to protect patients or hospital equipment in these more-distant ashfall areas.

The closest health centres to Volcán Tungurahua reported various effects of volcanic ash on the health centres, the population and on the services provided. However, none of the impacts affected the ability of the hospitals or centres to function, or to provide essential services. Ashfalls in general have not been sufficiently thick to cause roof or gutter damage at these locations from past eruptions.

The following passages discuss the consequences of ashfall on healthcare centres in the Tungurahua volcanic area, to highlight the variety of issues that arose during oral accounts. The amount of ashfall has varied across these locations, due to distance from Volcán Tungurahua and the orientation of the plume. The facilities and services provided at each of the health centres are also variable; scaling up from health subcentres, to centres of health and basic hospitals.

3.3.4 Lifeline utilities

Overall there were no reported access problems associated with travel to and from health centres, there were no power cuts caused directly by ashfall that threatened the provision of essential services, and communications systems were not generally affected. However the private clinic in Baños recalled a loss of power when lahars impacted power lines at the base of the volcano in 2006. Water supplies at hospitals and health centres for the most part are covered or piped from reservoirs distant from the volcano and so remain largely unaffected by ashfall. However, on a country-wide scale, a PAHO official said that in general wastewater systems are not covered, and would therefore be susceptible to blockages from ashfalls. There have been no reports of blockages of wastewater systems at the health facilities, although in past eruptions drains have been said to have become blocked and required clearing of ash in order to prevent problems.

3.3.5 Impacts on public health and healthcare service provision

Discussions with healthcare professionals revealed that local populations have been found to suffer from digestive problems related to drinking ash-contaminated water and eating ash-contaminated food in region affected by ashfall. Centro de Salud Riobamba is a regional health centre and so has an overview of the effects of ashfall both in the city, and in several smaller towns within the region. According to the healthcare professionals interviewed, ashfall has caused a variety of skin, abdominal, digestive, psychological and respiratory problems. This is also found within the literature, where ashfalls have resulted in increased instances of short-term respiratory health effects in affected populations (Horwell and Baxter, 2006; Baxter, 1983).

In Penipe a hospital manager told us of a small increase in respiratory effects, skin allergies, conjunctivitis, and also problems associated with contaminated water and food, caused by ashfalls. In Pelileo a healthcare professional noted increases in respiratory effects and skin allergies from ashfall. The public hospital in Baños also noted in increase in nose, mouth and throat problems and respiratory effects for 2-3 months after the 1999 eruption. This hospital estimated that three out of every ten people visiting the facility were affected by these symptoms at this time. In the Baños private clinic patients had to wear ash masks inside the building at one point during the 2006 eruption, as ash was suspended in the atmosphere both inside and outside the building. Quero health centre noted that the service demand was higher in the early years for respiratory problems, but said that they no longer experience this kind of demand as people know now how to protect themselves. Healthcare managers in Guayaquil reported no increase in public health effects caused by the ashfall. However anecdotally, a non-health professional in Guayaquil said that there were about two days when people suffered respiratory irritation in Guayaquil following the eruption of May 28, 2010.

In addition to the short-term public health effects noticed from ashfalls, longer term psychological effects have been observed by medical professionals to have increased since eruptions began in 1999. A hospital manager in Riobamba estimated that there had been around a 50% increase in psychological problems since the eruptions began in 1999. There are additional reports in Baños, Puyo, Penipe and Pelileo that there has been an increase in anxiety and depression since eruptions began. This has been attributed to family stress caused by crop losses, evacuations and anxiety, by the healthcare professionals interviewed. Different clinics treat these conditions differently; some use medical treatments, others have started community work with their in-house psychologist, or counselling sessions.

Interviewees mentioned that during ashfalls there is an increased demand for GP services at hospitals, from respiratory effects and for optometry, and also that community counselling sessions that needed to carried out more often. There is also more demand for health information at the Baños hospital, and for basic medical supplies from the hospital pharmacy such as: vaseline, vitamin C, and personal protective equipment. A healthcare manager at Baños public hospital noted that increased attention was needed for some already-hospitalised patients during active times, as some vulnerable groups including pregnant women, children and the elderly, need more care at this time. In recent eruptions, 2006 and 2010, the public health impacts in Baños have been much less, as the population were more experienced in protecting themselves and more prepared for an ashfall (a hospital manager).

Despite an increase in public health effects from ashfalls noted by a healthcare professional in Penipe, the overall demand for health services reportedly decreased in this particular area during active periods. This was attributed to the population having other immediate concerns during eruptions; in particular farmers worried about their crops (a healthcare professional). And many people are thought to worry about a possible evacuation from the area during eruptions (a healthcare professional).

3.3.6 Impacts on buildings and equipment

Approximately 1-2mm of fine ash fell in Guayaquil during the 2010 eruption of Volcán Tungurahua. This was the most significant ashfall ever received in Guayaquil.

In Guayaquil, due to time constraints only one private hospital was visited, but there were no reported incidences of disruption to healthcare systems, or ash ingress into hospital buildings. However the hospital manager informed us that only 10% of the population would attend this hospital, and that most people would attend the public hospitals, which may have observed some consequences of the ashfall.

The only known incident of gutter replacement as a result of ashfall loading occurred in Pelileo following the 1999 eruption. In Baños public hospital, exterior roofs, gutters and drains have previously needed to be unblocked of ash (Baños hospital manager).

In Puyo, east of Tungurahua, there has been very little ashfall received over the years, and just a light fall was noted in 1999. In general there have been no reported problems at the health facility associated with ashfall. In Quero, west-north-west of Tungurahua, there is said to have been minimal ash received at the health centre during the 2010 eruption, but ash has ingressed into buildings during past eruptions and doors are now kept closed as a preventative measure (windows are already sealed at this centre). Occasionally protective masks or scarf's need to be worn in the Quero health centre to protect staff and patients from ashfalls.

In Pelileo ash does not ingress much into the building; windows and doors are closed and damp rags are placed under doorways, but no actions are required or taken to protect particular equipment. In Cotaló cardboard was placed under doors in the 2010 eruption to reduce ash ingress into the building, and other healthcare professionals have reported that protective measures were taken in Cotaló to reduce the impacts of ashfall. However no doctor or manager was available at Cotaló to interview at the time of our visit, and so more information about the effects of ash in this very proximal area to Volcán Tungurahua was not gained.

In Quero, computing and electrical equipment have been affected by ash blockages, but are covered in plastic for protection against ash during eruptive periods. No increased corrosion of equipment was observed or noted in association with any of the past ashfalls. In 1999 the ash was fine and entered into computers and photocopiers in Baños public hospital. Here, microscopes have been observed to become scratched by ash in the past, and are now cleaned by blowing air and using contact lens solution. Dental motors, compressors and electrical equipment have suffered blockages from ashfalls in past eruptions in Baños.

3.3.7 Ashfall clean-up

In 2006 approximately 50-75 mm of ash fell in Riobamba and since this event there has been an increase in communication and prevention, such that in 2010, "mingas" (groups of the general public in the community,) worked together to solve problems before they occurred and cleaned up the ashfall in the town. Ashfall received in Riobamba in 2010 was approximately 1cm thickness. All essential services in Riobamba have continued to function during ashfall events. In Penipe health centre, not much ash has come inside the building but a specialist cleaner is contracted to clean the roof after an ashfall. In Baños public hospital increased cleaning was needed following ashfalls and medical equipment was maintained by cleaning and vacuuming, which is carried out daily to weekly in active times compared to every 2-3 months normally. In Quero ash infiltration into the health centre required increased cleaning efforts on a daily basis during ashfalls.

3.3.8 Economic impacts

During eruptions there are economic impacts on the health service. These arise as hospital staff has had to work increased hours, as hospital operating hours lengthen during heightened volcanic activity. This incurs increased salary costs. Additionally the moving and rationing of food for shelters incurs increased costs. Money is also spent in non-eruptive times on advice campaigns for recommended actions to take during ashfalls and eruptions (Riobamba hospital manager). Increased supplies of masks and preventative and protective equipment also incur additional costs to health facilities.

3.3.9 Physical back-up systems and energy use rationing

All facilities visited during fieldwork had back-up generators, although many were not sufficiently large to serve the entire health centre. Power supplies are prioritised during power cuts for essential services including emergency rooms and operating rooms. There were also reports of the number of lamps in use being reduced during power cuts in order to conserve energy consumption by the generator(s) (Baños hospital manager).

A knock-on effect has arisen from concern over power failures and their effect on refrigerated vaccines and medical supplies. During the 2006 eruption power lines were cut off by lahars and power to the facility was temporarily lost. No refrigerated supplies were unusable as a result of this, but this occurrence has led to the Baños private clinic no longer stocking temperature-dependent supplies. The medications are expensive and the risk to them is considered too high to warrant stockpiling supplies (a healthcare professional).

3.3.10 Building and physical modifications

A healthcare professional in the private clinic in Baños said that ash ingress had occurred in the past during eruptions when the clinic had a zinc roof. However the clinic has replaced the old zinc roof with a concrete construction. The healthcare professional attributed the ash ingress to the previous roofing style and reported no further ash ingress occurrences after the roof was changed to concrete.

Physical protective measures are undertaken at some centres including taping windows to protect glass from shattering as a result of volcanic sound waves. Additional protective measures include closing windows and doors, and in some cases using damp rags or cardboard under doorways to reduce ash ingress.

In Riobamba there is now an allocated “safe hospital”, which is a teaching hospital, to which people are encouraged to go during eruptions. This hospital has reportedly been evaluated and certified within Latin America as well equipped to cope with disasters (details of the evaluation criteria or certification body are unknown to the authors).

3.3.11 Protective equipment

Many health centres supply personal protective equipment to local residents including: masks, goggles, and vasoline, as well as creams, eye drops and asthma inhalers. In Quero, scarfs have been supplied instead of masks as a protective measure, as the masks are thin, get damp from breathing and do not last for re-use.

In general medical professionals in Baños reported that the population was now more prepared for ashfalls; they wore protective masks, goggles and caps in the 2006 eruption (some people also wore hard hats), compared to the 1999 event. Good community preparedness was also reported in the same way for the 2010 event.

3.3.12 Cleaning and maintenance

Cleaning methods for preventing scratches to microscopes have been developed at Baños hospital, including the use of contact lens solution. Routines for maintaining equipment during active times has been developed and vulnerable equipment has been identified, such as dental motors, which become blocked by ash getting into the operating mechanism. In

Quero equipment is covered in plastic sheeting for protection against ash. Other health centres mentioned that they had to increase the normal cleaning and maintenance of buildings during ashfalls.

3.3.13 Contingency plans and community work

The hospitals and clinics visited do have emergency or contingency plans in place. However in Baños hospital, the contingency plans are eventually overridden by the local emergency management plan, as the hospital would not evacuate unless the local government gave the order to do so. Precautionary steps are taken in the hospital in accordance with the activity level, with corresponding contingency plans, including; taping windows to prevent glass shattering from sound waves (slow onset, minor eruption), and wearing masks and protective gear if necessary. But if the evacuation order is not given then the hospital will remain open. Other health centres have several emergency plans; one for the health centre, one for the cantonal (a ‘cantón’ is an area smaller than a province,) and one for the province. Staff at the health centres visited are aware of the volcanic alert levels and the changes in routine required when alert levels are altered. They are generally well organised and there is a clear hierarchy of health centres in each region, to which patients would be transferred if necessary.

In most centres staff members are trained in disasters and form “brigades”, a group of medical professionals who work in the affected communities at the shelters or by assisting health centres in the most affected areas. These Brigades are formed by staff at most of the health centres visited in the Tungurahua volcanic area. Education in schools is also carried out by some health centres. There has also been an increase in counselling sessions in some areas to provide psychological assistance to the affected population. The Red Cross also started a programme in high risk areas called “Back to Happiness”, after a peak in depression was noted in affected populations 3 years after the 1999 eruptions (Risk Manager in Baños).

The hospital manager in Baños said that by the time of the 2010 eruption there were evacuation plans, people conserved food and they had undergone training in skin and eye care. There appears to have been a general trend of greater community preparedness over time in the affected areas.

3.4 Transportation networks

3.4.1 Roads

In general, ashfalls from eruptions of Volcán Tungurahua since 1999 have caused few problems for road transport networks. However, frequent lahars from Tungurahua have caused road and bridge washouts, particularly during the rainy season (February to September). During these months, heavy rains fall on the Ecuadorian highlands. These can entrain unconsolidated volcanic material deposited on the upper slopes of the mountain which can form lahars. Roads traversing the base of the mountain are particularly vulnerable. The road from Penipe to Baños was cut at the time of fieldwork as a result of mudflows. Another vulnerable location is the area called Juive Chico, immediately west of Baños. Major lahars in 2006 buried houses, covered the road and washed out a bridge (Figure 15).

Figure 15 Area of lahar damage in Juive Chico, west of Baños (GPS 16). Upper photo: new section of road replacing lahar-damaged section. Lower photo: in same area, house buried by lahar deposits.

3.4.2 Aviation

The May 28 2010 eruption of Volcán Tungurahua deposited approximately 1-2 mm of fine-grained ash on the city of Guayaquil. This city rarely experiences ashfall and was therefore not well prepared. This ashfall was sufficient enough to warrant closure of José Joaquín de

Olmedo International Airport for two days as flights were grounded. Cleaning crews were dispatched to sweep up ash into piles where it was bagged and then taken to a landfill site located 16 km outside of the city. Unofficial reports suggest that approximately one thousand bags of ash were collected during the cleaning efforts (Instituto Geofísico, pers. comm.[2]). Unfortunately we were unable to schedule an interview with the airport management to obtain further details.

3.5 Municipal clean-up and ash disposal

The National Secretariat discussed general approaches to ashfall clean-up across ash-affected regions. In general, brooms are used for clean-up of streets if the grain size of the ash allows. Once swept up, a truck provided by the local mayor will collect the ash. The National Secretariat assist the local level authorities by providing bags for ash collection; ask mask supplies, and goggles and brooms to assist the clean-up. Groups of the local population called ‘mingas’ generally maintain infrastructure and roads within the community, and will clear ash within their neighbourhood. However for the clearance of roads that run between villages, the provincial level are responsible for the clean-up. The municipality and the National Secretariat share the cost of clean-up, by an agreed proportion that depends on the situation; the cost is split so that 50% is paid by the Municipality and 50% by the National Secretariat for routine maintenance (this may include landslides, mudflows or lahars), but in emergencies the National Secretariat will pay 80% of the total cost, with the municipality making up the remaining 20% of the cost.

Some information on cleanup operations in Guayaquil was obtained (Municipality of Guayaquil environmental scientist). The municipal cleanup was reportedly a minor operation performed mostly by residents using brooms. No extra water demand was created. At the international airport, cleaning crews were dispatched to sweep up ash into piles where it was bagged and then taken to a landfill site located 16 km outside of the city. Unofficial reports suggest that approximately one thousand bags of ash were collected during the cleaning efforts (Instituto GeofísicoGeofísico, pers. comm.). For the city of Guayaquil, ash was disposed of at a landfill site outside the city (Las Iguanas) and an island off the coast.

3.6 Telecommunications

Recounts from the last 11 years of volcanic activity at Tungurahua suggest that telecommunications are vulnerable to hindrance from volcanic ash plumes. In particular, Instituto GeofísicoGeofísico Volcano Observatory noted radio attenuation and reduction of broadcast signal strength when receivers located on the volcano became coated in ash. However the phenomena is not well understood nor well documented in other eruptions. There have been numerous examples of telecommunications transmissions continuing to work during volcanic ash falls and a recent analysis by telecommunications engineers for the New Zealand-based Auckland Engineering Lifelines Group concluded that impacts on electromagnetic signal transmissions would probably be limited to low frequency services such as satellite communications (Wilson et al., 2009). Conversations with electricity personnel revealed that fiber optic communication systems perform flawlessly during ash events unless damaged directly by falling volcanic bombs.

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[2] Comments made by individuals that were not recorded during formal interviews have been referenced anonymously and noted as personal communications (pers. comm)

4.0 IMPACTS ON AGRICULTURE

Owing to the tight time constraints of the field visit, determining agricultural impacts of the 2010 eruptions of Tungurahua was not a major focus of the field work. However, general information on impacts on agricultural production was obtained from the National Secretariat and was mentioned by others interviewees. A field visit was made to the town of Cotaló, which received ashfall during the 2010 eruptions, as well as during the previous decade of volcanic unrest, particularly in 2006.

4.1 Overview of agriculture in the Tungurahua area

Volcán Tungurahua is surrounded by high-density agricultural land (Figure 16). Locally-grown crops include maize, beans, potatoes and onions (these four constitute approximately 80% of the crops in the Tungurahua region), as well as citrus fruit, avocadoes, bananas, flowers, and sugar cane. Livestock activities include dairying and intensive chicken farms (Leonard et al., 2005). Most farms are smallholdings (80-90% of farms in the region are estimated to be less than10 ha).

Figure 16 Intensive land use on lower slopes of Volcán Tungurahua (photo taken from near Cotaló).

In Ecuador, the growing season is virtually continuous throughout the year due to its equatorial location and climate. Plants are harvested when mature, which can be at any time of year. Thus, in the event of an eruption there will be crops at varying stages of maturity, which in turn affects their vulnerability to ashfall (Wilson et al. 2006). These authors note that there is, however, no general relationship between stage of development and vulnerability to ashfall damage. For instance, rice was found to be more vulnerable during mature stages with seed heads easily damage, but corn was vulnerable during early to mid-stage development and relatively resilient when mature. Other plants such as tobacco are vulnerable throughout their life cycle.

These authors also noted that different crops have markedly different vulnerability to ashfall. In general, root and low-growing vegetables such as carrots, onions, potatoes and cabbages are the least vulnerable to ashfall. Plants with shiny or waxy leaves, such as cabbages, appear to be able to shed ash easily. Plants with large leaves, such as bananas and corn, are particularly vulnerable, as are plants with sticky or hairy leaves such as tobacco and tomato plants. These leaves are thought to be efficient traps for ash.

4.2 Impacts of ashfall and adaptations in the Tungurahua area

The National Secretariat provided us with the following summary data on the impacts of the 2010 eruption of Tungurahua on agricultural land (Table 3).

Table 3 Impacts of on agricultural land.

Province	Canton	Area partially-damaged (ha)	Total damage (ha)
Tungurahua	Baños	1086	5
	Pelileo	475	20
	Quero	300	0
	Mocha	1207	0
Chimborazo	Puela	672	0
TOTAL		3740	25

According to the National Secretariat, impacts of the 2010 eruptions were minor in comparison to the impacts experienced in 2006. In 2006, maize and banana crops were particularly affected. It was also found that plants that had been sprayed with insecticide were more vulnerable to ash damage as the ash adhered to the spray. These crops were ruined, but were put to further use both as animal feed and by being mixed with soil to make compost.

Some of the adaptations implemented in response to the volcanic unrest are: farmers moving towards planting more resilient crops such as onions; livestock are only reared in the region for short periods of time to limit problems with tooth abrasion; and greenhouses have been constructed in Cotaló and other centres to protect crops.

4.3 Case study: Cotaló

The village of Cotaló is located approximately 8 km NW of the summit of Volcán Tungurahua, on the opposite bank of the Rio Chambo (Figure 10, Figure 17 and Figure 18). During our visit we spoke informally to the owner of a chicken farming business and to a local government official.

Figure 17 General view of Cotaló (at far end of terrace) and surrounding area.

Figure 18 Entrance to village of Cotaló.

A wide range of crops are grown in this area, including pasture grass, potatoes, carrots, maize, onions, lettuce, cabbage, beans, guavas, peaches, apples, tamarillos, ‘claudias’ and ‘capolitas’.

Due to its location immediately downwind of Tungurahua, Cotaló has experienced impacts from volcanic activity since 1999. It suffered the most significant damage in 2006. Cotaló is comprised of 9 smaller sub-communities; two of these (Pillate and San Juan, located on terraces above the river to the south of Cotaló) were the worst-affected. Sometimes, during our conversations with local people, it was difficult to differentiate which events were being referred to.

4.4 Impacts of earlier eruptions

Local people estimated that 20-40 cm of ash was deposited in Cotaló during the 2006 eruptions. Incandescent blocks also fell on the village, and caused major damage to roofs, and building collapses (Figure 19 and Figure 20). A local farmer estimated that 50% of roofs in the town were damaged and needed to be replaced. She also mentioned that the ashfall caused some corrosion damage to roofs.

Figure 19 Ballistic block damage to shed roof, Cotaló, 2006 (photo courtesy of Carlos Fernando Perez).

Figure 20 Ashfall on ground, Cotaló, 2006 (photo courtesy of Carlos Fernando Perez).

There were apparently few problems with the town's water supply, which is piped from nearby hills. There was a power outage on the day of the eruption, but it lasted less than a day.

In terms of agricultural impacts, local farmers reported that 'animals died' from ingesting ash. However we were not able to obtain further details about the nature of the impacts of the ash, the type of livestock affected or how many died. Impacts on crops were severe with almost all crops lost. Very little could be grown in the following two years; seeds were planted but failed to thrive. Nothing could be grown for two years afterwards. The ash was tilled into the soil using cattle-drawn ploughs, to about 40-50 cm depth. Larger blocks were a problem initially but apparently they are quite friable and break down readily in the soil.

We spoke to a local chicken farmer who has 12,000 birds housed in four sheds (Figure 21). They produce on average 10,200 eggs per day. In 2006, the business had three sheds, of which two collapsed following the eruption. The long span of the roofs was apparently a problem; when the sheds were rebuilt, beams were reinstalled with more closely-spaced crossbeams (1.5 meter spacing, reduced from three metre spacing). Minor ballistic damage was patched up (Figure 22). The birds were uninjured by the eruption despite the damage to their sheds, but were apparently unnerved by it to the point where egg-laying ceased entirely for one month. During this time they were given sedatives and extra vitamins.

This farmer suffered a 60% loss in income for the year following the eruption. This was mostly due to the costs of repairing the buildings, and the disruptions caused by having to clean all the debris out of the sheds. They had to survive on their savings, but were 'back on their feet' by 2008. There were no loans available from the government to help rebuild.

Figure 21 New sheds (rebuilt after 2006 eruption) housing chicken farm, Cotaló.

Figure 22 Ballistic damage to the roof of a chicken shed.

4.5 Impacts of the 2010 eruption

The 28 May 2010 eruption deposited some ashfall on the Cotaló area. Estimates by locals of the quantity of ashfall ranged from 3-4 cm to 3 mm. It did not cause any physical damage to buildings.

Livestock was pre-emptively evacuated to Pelileo so animals could have uncontaminated feed; there was no supplementary feed available for them in Cotaló. This was paid for by the municipality using emergency funds. Cattle were apparently fed on ruined fruit (bananas) shipped up from the coast. There was some damage to crops, but local farmers were able to harvest approximately 70% of crops. Some were found to be more resilient, particularly potatoes and pasture grass.

5.0 VOLCANIC EMERGENCY MANAGEMENT IN ECUADOR

5.1 Emergency management structure

This section gives an overview of the structure of emergency management from the national through to the local level in Ecuador. This section also discusses the plans for change in the emergency management system.

Much has changed with regard to emergency management since the previous GNS research trip to Ecuador in 2004 (Leonard et al., 2005).

The Secretariat Nacional de Gestation de Riesgos (National Secretariat of Risk Management), otherwise referred to as the ‘National Secretariat’, was formed in 2008. It was created as an umbrella agency that incorporated Civil Defence, but broadened its scope from the traditional emergency response role, to include risk management and disaster risk reduction. Civil Defence remains as a small role within the agency to deal with emergency response, and includes mainly volunteers (vigìas) who are linked at the local level.

As discussed in Section 0, the procedure for emergency management involves a three-step process. In a state of volcanic unrest, IG monitors the activity and develops hazard scenarios, which are passed on to the National Secretariat. The National Secretariat uses the hazard scenarios and develops contingency plans that are then passed on to the local government. It is the local government mayor who makes the decision regarding the appropriate alert level, and also whether or not to order evacuations.

There are procedures in place to assist the mayor or local government in decision making, which are outlined in “Emergency Plan of Action” documents. Emergency plans of action at the local level include four main components (translated and summarised from: National Secretariat, Emergency plan for the cantonal of Pelileo, post 2006):

1. The COE (Committee of Emergency Operations*) is the executive level of decision making at the Cantonal or Provincial level, depending on the severity of the situation. The COE works with the Secretariat of Risk Management technical office and provides needs and damage assessments, as well as evaluating local resource capabilities.
2. The Technical Area is occupied by the Position of Unified Command, which organises and allocates functions and work streams to each area of action necessary, depending on the capability of each institute. These institutes and areas of work include: evacuation areas and areas for shelter, security, food, engineering, water, communications, infrastructure, fire brigade, Civil Defence, the Red Cross, and the army, The Position of Unified Command works with the COE, exchanging information and executing the decisions of the COE.
3. The Administrative Area works on the economics and finances, and coordinates operations and logistics. This area also distributes external aid/ funds.
4. Coordination Units correspond to the provincial Secretariat of Risk Management technical office that provides experienced operating and administrative personnel to act as coordinators across the COE and the Position of Unified Command.

*The COE used to stand for the ‘Centre of Emergency Operations’, however the National Secretariat has changed this to the ‘Committee of Emergency Operations’. This was done to emphasise that engagement and communication at the local level are key to the decision-making process, and that these actions are not tied to a physical location (or centre) - meetings will occur at the local level, wherever that may be.

The emergency plan provides the following guidelines and protocols for action:

- Guidelines for activating of the COE, which include: receiving information from IG informing the mayor about volcanic activity; the mayor will form a local COE and assign the alert level; the capacity of local resources will be assessed and if exceeded, the mayor will request assistance from the provincial governor, who will act in accordance to the Plan of Action; the provincial COE will be formed from the directors of different work areas, and the Position of Unified Command will be set-up.
- Decision trees for allocating the alert level based on information from IG, and with guidelines for assigning each coloured alert level (yellow, orange, red) depending on the hazards faced.
- Guidelines for actions to be taken for certain hazard scenarios.
- Protocols for action in each of the functions or work streams (e.g. for setting up shelters, managing security, food etc.).

The Emergency Plan of Action for Pelileo contains specific guidelines for actions to be taken during ashfall (National Secretariat, post 2006). These are outlined as follows:

“To provide to the population the necessary supplies to reduce the effects of these phenomena [ashfall] such as: water, food, masks, scarfs, eye drops for the eyes, and to distribute information about the precautions to take for their protection and that of their goods. For the case of the animals fodder for its diet will be delivered and/or transfer to less affected zones.” (National Secretariat, Emergency Plan for the cantonal of Pelileo, post 2006).

A local risk manager in Baños reported that the contingency plan is being revised following the May 2010 eruptions and that these plans are always being revised to keep them up-to-date.

In practice, the process of emergency management is less fluid, and the decisions made at local level are affected by socio-political circumstances. Accounts have been given during fieldwork of red alerts being assigned in local areas, but no actions taken with regard to evacuations or access restrictions. These actions are outlined as the appropriate response in a red alert according to the Emergency Plan of Action (Medical Professional in the Penipe area). Other reports have been made of local road clearances being carried out by mayors, on high risk roads that have been blocked by landslides, lahars or mudflows, in order to keep the fastest routes to market open. These are examples of complex decision-making driven by local needs and pressures.

Local level decisions are also constrained by resources and experience in emergency management decision-making. To this end, the National Secretariat is setting up training programs for decision-makers in emergencies, to better enable them to take the lead in emergency situations (National Secretariat manager).

The National Secretariat is revising its procedures following recognised short-falls in the current alert levels and contingency plans. It has been noted that alert levels are inconsistent across municipalities, and Volcán Tungurahua itself is divided into two provinces: Tungurahua and Chimborazo. Plans are being made to unify the alert level system and connect appropriate decisions, actions and procedures to the alert level. It has also been identified that the current contingency plans do not link the hazard scenarios well enough to guideline actions at the local level. This results in local government decisions being made but without appropriate actions being taken. These revisions to the current procedures are expected to be updated by the end of the year 2010. Additionally, the National Secretariat wants to set up relocation exchange programmes between towns, so that people know where to go to in the event of an evacuation (National Secretariat manager).

5.1.1 The role of vigìas in the area around Volcán Tungurahua

Vigìas (volcano observers and local voluntary civil defence) perform essential tasks during heightened activity and are key to both hazard assessment and emergency management in the area surrounding Volcán Tungurahua.

One of their duties is to report their observations of hazards to Instituto Geofísico (IG). Vigìas are equipped with radio communications and call signs, to report any hazard observation to IG at Tungurahua Volcano Observatory (TVO), Guadeloupe. There has been a code developed to communicate the observations and hazards effectively and with correct terminology. Vigìas ground-truth activity with their observations and report this to IG.

In addition to their voluntary roles, vigìas are also paid on an ad-hoc basis by IG to clean solar panels at the monitoring stations when these become covered in ash. This is an essential service to ensure continued monitoring capabilities at the observatory (TVO) and vigìas are paid a fixed sum per panel cleared of ash.

The main role of vigìas is voluntary civil defence. They are usually community leaders, who have been trained in emergency preparedness and response. The vigìas train with the emergency services and Red Cross, and communicate with the army, police, fire brigade and IG as appropriate. They are equipped with radio communication systems, personal protective equipment and are trained to give advice to the local community about preparedness and emergency actions.

Vigìas are considered essential to the process of assisting the community in preparation and in emergencies. IG at Tungurahua Observatory said that vigìas help with communications and evacuations, and that their status as community leaders ensures that evacuations are more successful as more members of the local communities respond and self-evacuate.

5.2 Emergency management practice around Volcán Tungurahua

Since the reactivation of Volcán Tungurahua in 1999, emergency shelters have been set-up in safer areas, close to the communities at risk. The shelters provide food, a place to sleep, and are visited by medical professionals to provide basic medical care, medicines and psychological support. A photograph of a shelter near Penipe is shown in Figure 23.

Figure 23 Emergency shelter near Penipe, Tungurahua area.

The National Secretariat has organized signs and evacuation routes to inform local populations where the nearest shelters are located in emergencies (see Figure 24 and Figure 25).

Figure 24 Emergency muster point signage in Penipe.

Figure 25 Evacuation route signage in Cotaló.

5.3 Community response to volcanic unrest

This section discusses the community response of communities close to the volcano when volcanic unrest occurs. Many of these communities have received ashfalls intermittently, and been at risk from other volcanic hazards such as pyroclastic flows and lahars, since the reactivation of Volcán Tungurahua in 1999.

The response of people at the local level is driven by their everyday needs as well as by the risks that they face. In general, some communities have been known to auto-evacuate during times of unrest, particularly noted during the 2010 eruption of Volcán Tungurahua (National Secretariat). However, a healthcare professional informed us that farmers in particular will return to their homes during the day to tend to crops and animals, and others will also return to check on their properties. At night, most people will sleep outside the high risk area, returning only in the daytime. As a consequence of this, healthcare professionals in the region generally attend the shelters in the evenings, between about 5-7pm, which is when most people arrive for food, shelter or medical attention.

The National Secretariat provided a table of the capacities of local shelters, and the data of how many families attended the shelters from 28th May-14th June 2010. This is reproduced in Table 4. Each of the Cantons has several shelters, each with varying capacities according to their size. Small villages attend the shelters in the nearest larger village or town that is outside of the evacuated area.

Table 4 Capacity of shelters in the provinces and cantóns close to Volcán Tungurahua, and the number of families staying in the albergues (shelters) from 28th May to 14th June 2010. Reproduced courtesy of the National Secretariat of Risk Management, Ecuador.

PROVINCE	CANTÓN	NAME OF ALBERGUE (SHELTER)	CAPACITY (PERSONS)	BENEFITTING COMMUNITY	NO. BENEFITTING FAMILIES *
TUNGURAHUA	PELILEO	Áreas comunales del reasentamiento de La Paz	100	Chacauco	5
				Cusúa	15
		Casa parroquial de Cotaló	75	Bilbao	15
		Albergue Pelileo - MIES	250	San Juan, Pillate	50
		Queseras	100	Queseras	
		Huambaló	120	Huambaló	
		Albergue Centro San Liborio	50	San Liborio	
	BAÑOS DE AGUA SANTA	El Aguacatal (Centro de Albergue Temporal - CAT)	150	Pititig	10
		San Vicente	250	Las Ilusiones (Bascún)	100
		Casa comunal de Río Blanco	50	Juive Grande	3
		ISPED (CAT)	2000	Parroquia Matriz de Baños	
		Escuela de Policía	300	Parroquia Matriz de Baños	
	QUERO	El Santuario	100	El Santuario	20
		Colegio 17 de Abril	200	Quero centro	
		Escuela de Policía	200	Quero centro	
CHIMBORAZO	GUANO	CDH	50	Ilapo	
		Múltiple	200	Centro de Guano	
	RIOBAMBA	Múltiple en Ciudadela Sixto Durán	200		
		SPOCH			
		Brigada			
	PENIPE	CDH parroquia El Altar	50	El Altar	
		CDH cabecera cantonal	50	Penipe	
		Múltiple	200	Penipe	

5.3.1 Baños: a unique case of preparedness and social response

On the 18th October 1999 the city of Baños and surrounding farmlands were ordered to evacuate by authorities following the reactivation of Volcán Tungurahua and advice from the scientific community that the city was at risk from volcanic hazards. The city was forcibly evacuated and remained guarded by the army and police to prevent people from returning to their homes and into the area at risk.

However, after many weeks of evacuation and despite several eruptions from Volcán Tungurahua, there was no significant damage in the city of Baños or its surrounds. The local inhabitants wanted to return to their homes and their livelihoods, having suffered severe socio-political disruption from the evacuation orders (Tobin & Whiteford, 2002). On the 5th January 2000 the townspeople marched to Baños and clashed with the army to try to win the right to return home (Lane et al., 2003).

Following this, provincial mayors then signed a document allowing people to return to their homes but at their own risk. Local people from Baños responded by forming a group to inform people of what they should do in emergencies – this was the start of the vigìa system and the voluntary civil defence (Risk Manager in Baños).

For a more detailed account of the Baños evacuation in 1999 and the subsequent recovery, see Leonard et al. (2005).

There have been no evacuation orders issued in Baños since the 1999 eruption. This is despite heightened activity and significant eruptions in 2006, including ballistics falling in the Baños area. The volcanic activity in 2006, in the opinion of some interviewees, should have prompted an official evacuation of the city.

Following the reactivation of Volcán Tungurahua in 1999, the local population painted yellow arrows on the roads in Baños with donated paint, to mark evacuation routes. Since this, the National Secretariat has altered the Baños signs to correspond to those in other areas around the volcano. The old yellow road markings are now painted green, and as in other areas, there are signs with distances to shelters and ISO signs to indicate the area at risk from volcanic hazards.

A vigìa in the Baños area explained that the evacuation plan used to be simple, but now it is complex and possibly confusing.

In Baños new warning sirens were installed in September 2010, following the May 2010 eruptions. These sirens were trialled by local people and have two distinct sounds; one for a drill (intermittent siren), and one for a real event (continuous siren). The sirens also have batteries that are connected to electrical transformers so that they are always charging. This ensures that these are fully charged should a power cut occur (Risk Manager in Baños). This back-up power supply to the sirens has been a recent adaptation, as a risk manager told us that in 2006 the sirens would not have worked in some lower risk areas of Baños, due to a power cut and a lack of back-up power supply to the sirens. As a result of this, there is now a back-up plan written into the contingency plan, where police and firemen will drive around the city sounding their sirens to alert the public should the sirens fail. The risk manger clarified that it is the mayors' decision to sound the sirens, and the mayor did not initiate the use of this system in 2006.

In general the evacuation routes are clearly marked with signs and road markings throughout the city, although many shelters are some distance from the town at more than 2 km away. A photograph taken in Baños of the routes to emergency shelters is shown in Figure 26. Drills are also carried out in the town to ensure that people are practiced in emergencies.

The designated safer area in Baños is to the east of the city, and in drills it takes 16-17 minutes for the population to reach the area where the shelters are located. Approximately 80% of Baños towns-people are said to be trained for evacuations and know, for example, not to cross bridges over rivers in times of eruption (a Vigìa in the Baños area). However the vigìa also remarked that the safer area in the east of Baños is still very close to a river valley that could potentially carry pyroclastic flows or lahars from the flanks of the volcano. Each family is also said to unofficially have their own family contingency plans (a vigìa in the Baños area). Thus despite evacuation planning and drills, individual or family actions may differ from the officially planned scenarios.

Family actions in emergencies include shutting windows and doors and locking-up their houses. Additionally turning off the electricity, and covering water supplies for protection against ash ingress and contamination (a vigìa in the Baños area).

Some of the population of Baños auto-evacuated during the increased volcanic activity in May-June 2010, returning only in the daytime to check on their property or animals, and sleeping outside the high risk area at night. This auto-evacuation of the population is a positive step in emergency management, where awareness and responsibility are carried by the owners of the risk – the population.

However, there is a downside to the auto-evacuations. It has been known that hotel owners have locked visitors inside the hotels during periods of heightened activity, and auto-evacuated themselves from the area (a scientist). This reportedly occurred during heighted volcanic activity in both 2006 and 2008, as owners attempted to protect their income so that people could not leave without paying. As a result of these actions, civil defence was forced to rescue trapped visitors from hotels using ladders.

Figure 26 Signs marking the routes to emergency shelters, taken in Baños (September 2010).

In general the population have adapted well to ashfalls and wear protective clothing including: masks, goggles and caps, and some people wear hard hats during eruptions.

A hospital manager in Baños said that people generally feel safe in the city, as no event has been significant enough to cause damage in Baños itself. People tend to assess their risk based on their observations of the volcano and act accordingly. Care should be taken that the community does not become complacent about their risk, or the risk to visitors, based on past experience of limited physical impacts in the town.

The history of the evacuation in 1999 and the success of a rebellion against the evacuation order has strengthened community ties in Baños (a vigìa in the Baños area). People are aware that they are living in Baños at their own risk, and reports of auto-evacuations of communities at times of volcanic unrest testify to this awareness. Overall ownership of the risk by the town members appears to have prompted an organised and more prepared society in Baños. However, comments made by locals about the potentially confusing changes to the evacuation plans as they become more complex, and doubts as to the safety of the Baños refuge area, should be taken into consideration by local officials and emergency managers.

6.0 CONCLUSIONS AND KEY FINDINGS

The key findings of this report are as follows:

- Since its reactivation in 1999, activity at Volcán Tungurahua has been mostly characterised by eruptions of low to moderate explosiveness. However, in 2006 there was a sudden increase in explosiveness leading to two pyroclastic flow-forming eruptions on 14 July (VEI 2) and 16-17 August (VEI 3).

Infrastructure impacts key findings

- Ecuador's 4000 MW electricity transmission did not experience any faults from volcanic ash contamination during the May 28 2010 Tungurahua eruption.
- The city of Guayaquil was coated in 1-2 mm of fine-grained ash and local substations had to be cleaned to prevent unplanned interruptions from insulator flashover.
- Cleaning of substations was performed strategically so that power supply was not interrupted for the city of Guayaquil. This was achieved by cleaning transformer banks individually, allowing all circuits to remain online.
- Insulators, towers and conductors were not cleaned as it was believed that rain and wind action would sufficiently clean these components and thereby avoid flashover.
- It was commonly believed by Ecuadorian power personnel that vertically configured insulator strings are more vulnerable to ash-induced insulator flashover over those in the horizontal position.
- Conversations with electricity personnel revealed that fiber optic communication systems perform flawlessly during ash events unless damaged directly by falling volcanic bombs.
- The Agoyan dam facility did not suffer any adverse effects from the May 2010 ash fall but has systems in place to monitor water levels and turbidity to trigger a protective bypass system in the event of a lahar.
- The ashfall reportedly caused problems with water supplies in the depositional area, which in turn led to health problems such as digestive upsets. However, the cause of these health problems was not clear. There is a new health ministry initiative to cover and protect water supplies from ashfall. In Guayaquil, 1-2 mm ashfall did not cause any problems for the municipal water supply, although supply outages of up to one day in each sector were implemented for precautionary cleaning of filters.
- Transport – ashfalls have caused few problems for road networks, but lahars have caused major problems particularly for direct route between Penipe and Baños. No particular impacts arose from the 2010 ashfall. However the 1-2 mm of fine-grained ash that fell on Guayaquil was enough to warrant closure of José Joaquín de Olmedo International Airport for two days as flights were grounded.
- Radio attenuation and reduction of broadcast signal strength was noted when receivers located on the volcano became coated in ash.

- The National Secretary helped the local mayor in each affected municipality by providing bags for ash, ash masks, goggles and brooms to affected areas.

- Ash collected by trucks was taken to a landfill site outside of Guayaquil (Las Iguanas) and to an island off the coast of Guayaquil.

Agriculture and rural communities

- The 2010 eruption caused partial damage to 3740 ha and total damage to 25 ha of farmland in the depositional area.

- In the case study settlement (Cotaló), impacts on livestock were minimal as animals were pre-emptively evacuated out of the affected area so they could have uncontaminated feed. There was some damage to crops but farmers were able to harvest approximately 70%. Estimates of ashfall depth in Cotaló in 2010 ranged from 3 mm to 3 cm.

- Cotaló suffered much more severe impacts from the 2006 eruptions. Many buildings were damaged by ballistic blocks (and, to a lesser extent, ashfall) with 50% of roofs in the town requiring replacement. Estimates of ashfall depth ranged from 20-40 cm. Livestock died from ingesting ash. Almost all crops were lost and nothing could be grown for two years afterwards. A chicken farmer lost 60% of their income in the year following the eruption, with most of the costs arising from having to repair buildings.

- Some of the adaptations implemented in response to the volcanic unrest in the local area are: farmers moving towards planting more resilient crops such as onions; livestock are only reared in the region for short periods of time to limit problems with tooth abrasion; and greenhouses have been constructed in Cotaló and other centres to protect crops.

Healthcare key findings

- Healthcare systems have shown preparedness in their development of emergency management plans and in the organisation of ‘brigades’ of medical professionals who attend shelters and carry out community work in affected areas.

- Physically healthcare systems have conveyed that there are limited impacts of ashfall to their essential service provision and to their critical utility providers. As such interdependency between impacts, which can cause indirect impacts on systems, has been minimal. However, as many health centre generators are not large enough to provide full services during power cuts, non-essential services are not prioritised and may be affected.

- Smaller effects of ashfall related to ash ingress have occurred in some locations, and measures are being taken to reduce ingress, protect windows, protect equipment, and to maintain and clean elements within healthcare buildings.

- Increases in respiratory effects, skin allergies, eye infections and digestive problems have been noted in most locations. Many public health pathologies have been reduced over the years as the population has taken preventative measures such as wearing goggles, and either masks or scarf’s during ashfalls.

- Increases in anxiety and depression in the affected population has been noted at most health centres as a long term impact of volcanic activity. This has been attributed to family stress, relating to loss of crops and income and from the concern over evacuations. This has prompted increased psychological support, which is provided by the healthcare centres, through medications, clinical psychologists or community work in the shelters.

Emergency Management

- The population is well adapted to the risks posed by the volcano; auto-evacuations and measures taken to protect themselves, such as wearing masks, goggles and hats, are testament to this.

- The participatory role of vigìas in both hazard identification and in civil defence, appears to have a positive effect on communication and risk management in the Tungurahua area.

- The National emergency management system is working towards improvement in the communication of risks between agencies and to the public. The changes to be made are not known at the time of writing.

- Officials in Baños have recently implemented a back-up power supply to the warning sirens, in case of a power cut during emergencies. There has also been an addition to the contingency plan for Baños, such that if the sirens failed to work, then the emergency services would drive around the city and sound their sirens to alert the public. This has been implemented following the power cut in 2006 that left the sirens unable to work, should the mayor have ordered the sirens to sound.

- Officials in Baños need to consider the concerns of locals about the complexity and confusion that may be caused by changing emergency management plans. Emergency managers should also consider the likelihood that in reality, individuals may choose alternative evacuation routes to those practiced during emergency drills.

General outcomes

- A good overview of ashfall impacts to electrical power and healthcare services, and emergency management issues were achieved during the trip. The information gathered adds to our knowledge of the possible effects of volcanic ashfalls on infrastructure and public services that have yet to be studied in depth in the literature. Emergency management insights may provide lessons pertaining the benefits of local engagement and involvement in risk management. Supporting insights and data were also found on other areas including: water and wastewater systems, agriculture and transportation networks. Focus on adaptations and responses to the long-term volcanic activity have provided insights into the long-term effects of volcanic activity and some possible mitigation and prevention measures.

7.0 RECOMMENDATIONS FOR FUTURE ASHFALL IMPACT STUDIES

Some lessons have been learned from fieldwork that can be taken forward into future, and recommendations are as follows:

- Overall there is benefit in returning to the Tungurahua volcanic area to accomplish ongoing research goals on volcanic ashfall impacts. There is rich data to be gained, and many areas of exploration that warrant further attention. Each sector of interest has its own methods and timeframes and not all can be explored in a single trip. More can be gained in several sectors from longitudinal studies in this area, in particular focussing on resilience and adaptations to ongoing volcanic activity.

- Timing of field trips is important to get right, to gain insights into the impacts of ashfall after the emergency response period is over, and before the effects lose resolution. It became evident during this fieldwork that the population considered the eruption in May 2010 to be minor, and therefore recalling the impacts and effects had lost some resolution by the time of fieldwork, some 4 months after the eruption. However, this is not the case in all events. It appears that for ongoing volcanic eruptions, unless a much larger event occurs than is considered to be 'normal', then the timing of fieldwork should be advanced, so as not to lose resolution on the data, particularly for qualitative data collection.

- In general, and particularly when there is a language barrier, field visits should be extended to allow more time to set-up interviews and meetings. More time in the field, particularly for long term volcanic eruptions and exploration of the adaptations made over time, will allow more observation time and a better understanding of the local context.

- Team size is critical, and more can be achieved by working in pairs, rather than as a whole unit. This requires more language support when working in foreign countries so that each pair of researchers is supported by a translator or interpreter.

- Financial support for fieldwork should be ring-fenced and determined pre-fieldwork. Whatever can be should be paid in advance of fieldwork. Working with 'one budget for all' considerably reduces unnecessary financial complications during fieldwork.

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APPENDICES

Appendix 1	Trip itinerary
Appendix 2	Data collection inventory
Appendix 3	Stream water quality data
Appendix 4	Scanned newspaper articles from the May 2010 eruption
Appendix 5	Ethics approval numbers

APPENDIX 1 TRIP ITINERARY

INSTITUTION VISITED	CITY LOCATION	DATE
Instituto Geofísico (IG)	Quito	06.09.10
TRANSELECTRIC head office	Quito	06.09.10
Pan American Health Organisation (PAHO)	Quito	07.09.10
Secretariat Nacional de Gestation de Riesgos (National Secretariat)	Quito	07.09.10
Baños Clinic [private]	Baños	08.09.10
Tungurahua Observatory	Guadeloupe, Baños	08.09.10
Local Risk Management, Baños	Baños	08.09.10
Agoyan Hydroelectric Dam, Baños	Baños	09.09.10
TRANSELECTRIC substation	Puyo	09.09.10
Ministerio de Salud Publica – Hospital “Puyo” [public]	Puyo	09.09.10
Ministerio de Salud Publica – Hospital de Baños [public]	Baños	10.09.10
Centro de Salud, Quero	Quero	10.09.10
TRANSELECTRIC substation	Ambato	10.09.10
Vigìa	Baños	11.09.10
TRAVEL TO GUAYAQUIL		12.09.10
TRANSELECTRIC substation	Guayaquil	13.09.10
Hospital in Guayaquil [private]	Guayaquil	13.09.10
Transelectric substation	Santa Elena	14.09.10
Ministerio del Ambiente (Ministry of the Environment)	Guayaquil	14.09.10
Ministerio de Salud Publica Subcentro de Salud de Penipe [public]	Penipe, Baños	15.09.10
Agriculture (general)	Cotaló	15.09.10
Ministerio de Salud Publica Centro de Salud Pelileo [public]	Pelileo, Ambato	15.09.10
Centro de Salud Riobamba	Riobamba	16.09.10
TRAVEL TO QUITO		17.09.10
FLY TO GUATEMALA		18.09.10

APPENDIX 2 DATA INVENTORY: RESOURCES GATHERED DURING FIELDWORK

Donated by	Type of resource	Details
Local administrator from Cotaló	Photos	Photos of earlier activity at Tungurahua in 2006 and 2007, photos of crop damage and roof damage
Baños public hospital	PowerPoint	Health plan for Area 4 (Baños) and Area 5 (Pelileo)
	Data	Annual summary of hospital admissions for types of illness (2001-2009)
	Report	Health plan for Chimborazo by Secretariat General
Riobamba Centro de Salud	Report	Emergency plan for Chimborazo
Riobamba Direccion de Salud	Data	Hospital admission statistics for 2007-2010
Private hospital in Guayaquil	News articles (HARD COPIES)	Articles on the 2010 eruption
Local Government Baños	Video	Lahar video (June 21st 2007)
	Map	Risk map of Baños
	Report	Red Cross guidance document for community volunteers on psychosocial support
	Report	Red Cross guidance document for community work to improve water quality and access to safe water
	Report	Red Cross action plan for a malaria epidemic and its consequences (Valle Hermosa area)
National Security and Risk Management (Secretariat General)	Presentation	Draft alert levels
	Presentation	Activity of Tungurahua 28th May 2010
	Report	Emergency plan for Pelileo region “cantonal”
PAHO	Report covers	Photocopies of report covers to find useful health guidance information online (HARD COPIES)
Pelileo Centro de Salud	2-pages Scanned	2-pages covering alert levels in a risk book
Private clinic Baños	Report	Emergency plan for the private clinic (HARD COPY)
Transelectric Quito	Map	Map of electrical transmission network
	Report	Emergency plan for volcanic eruptions for Transelectric
	Photos	Photos of ash cleaning

APPENDIX 3 STREAM WATER QUALITY DATA, TUNGURAHUA REGION

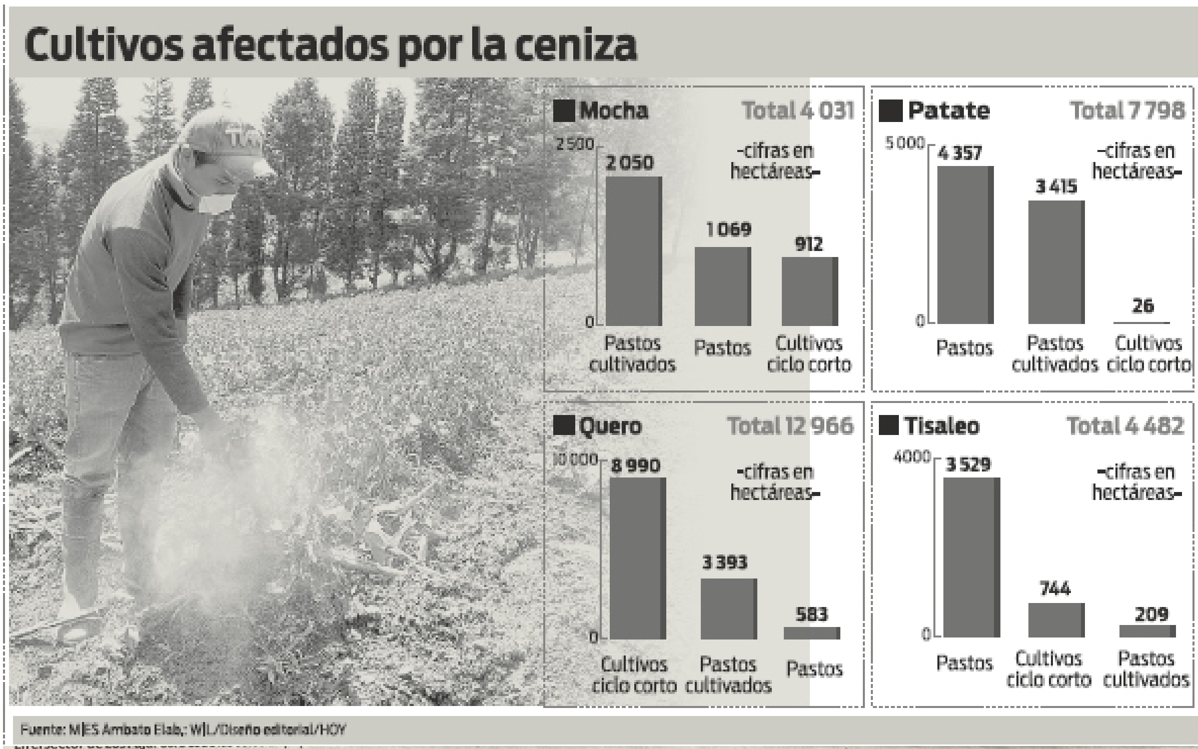
GPS	Location	Description	Date sampled	Temperature	pH	Conductivity	Turbidity
				ºC		µS/cm	NTU
2	1º 31’ 11.0’’ S 78º 29’ 27.4 ‘’ W	Rio Palitahua	15/9/2010	12.1	7	109.5	4.3
15	1º 24’ 21.6’’ S 78º 25’ 58.7 ‘’ W	Rio Vascún	16/9/2010	17.4	7.5	884	24.6
19	1º 24’ 3.7’’ S 78º 24’ 1.14 ‘’ W	Rio Chamana	17/9/2010	15.7	6.4	57.9	3.6
20	1º 23’ 44.5’’ S 78º 23’ 57 ‘’ W	Rio Ulba	17/9/2010	14.5	6.8	154	6.6

Figure A1 Rio Palitahua (GPS 2)

Figure A2 Rio Vascún (GPS 15)

Figure A3 Rio Chamana (GPS 19)

APPENDIX 4 SCANNED NEWSPAPER ARTICLES FROM THE MAY 2010 ERUPTION OF VOLCÁN TUNGURAHUA



60 familias evacuadas de Juive y Cusúa por la erupción del volcán

ECUADOR

En estas comunidades la gente salió por seguridad. Ayer, el coloso arrojó una columna de 10 km de altura. En el cantón Baños sigue la alerta amarilla.

Geovanny Tipanluisa. Redactor
Enviado a Baños

En el sector Los Pájaros, en el cantón Baños, 106 policías impidieron que la gente ingresara a las poblaciones Cusúa y Juive Grande.

Estas zonas se encuentran en un área de alto riesgo, a 4 kilómetros de Baños. Los bramidos de la 'Mama' Tungurahua, como dicen los campesinos al volcán, se escuchaban con fuerza. Una capa de ceniza cubrió los techos de las casas, calles, sembríos y todo.

Las autoridades informaron que el flujo de rocas pequeñas y piedras llegó cerca a estos pueblos. 60 familias evacuaron voluntariamente.

Silvia Mena, de 53 años, se llevó su cama, velador, ropa, la cocina, dos perros y sus pollos a La Paz, en el cantón Pelileo, donde se instaló un albergue. "Temprano, mi esposo ya se fue con mis chanchitos".

Jorge Guerrón, de la Unidad de Riesgos y Seguridad de la Policía, dirigió la evacuación. "Todo es voluntario, nadie les ha obligado".

Eso lo ratificó Francisco Argüello, quien también dejó su natal Cusúa, donde vive 65 años. En una camioneta subió sus pertenencias para trasladarse a La Paz,

volcán Tungurahua, que en la mañana arrojó una columna de ceniza de 10 kilómetros de altura, se escucharon en la ciudad turística donde habitan 16 000 personas.

Vasco aseguró que las explosiones ya no le asustan. Desde temprano, las radios locales anunciaban una evacuación masiva de turistas y pobladores de Baños.

Entre las 09:00 y las 11:00, en las radios se informaba que los turistas, especialmente los niños, estaban evacuando por precaución. Las autoridades de Baños indicaron que se dispuso que los estudiantes regresaran a sus casas como medida preventiva. También pidieron a los empresarios que explicaran a los turistas las rutas de evacuación.

Los buses que intentaban ingresar a la ciudad fueron retenidos por la Policía en Los Pájaros. El alcalde Hugo Pineda explicó que la medida se tomó por la caída de ceniza. Desde las 12:00, el paso de vehículos livianos y transporte urbano desde y hacia Baños se normalizó. A las 16:30, el bus número 35 de la Cooperativa Expreso Baños salió hacia Quito con 25 pasajeros. Luis Ojeda, uno de los despachadores, contó que luego de la erupción de la mañana la gente tenía temor.

En la calle Vicente Rocafuerte, en donde Vasco tiene su local, funcionan 20 negocios, entre restaurantes, hoteles, bares, etc. Todos trabajaron con normalidad.

El presidente de la Cámara de Turismo, Ángel Guevara, dispuso que los 5 000 operadores turísticos de Baños laboren sin restricciones hasta que el Comité de Operaciones de Emergencia emita una disposición.

La entidad, presidida por el Alcalde, se reunió desde las 09:00 en el primer piso del Municipio.

A las 16:00 se indicó que la alerta amarilla, adoptada tras la erupción de agosto del 2006, se mantiene y que por ahora se descarta que se declare una alerta roja.

Isabel Acosta estaba molesta, porque "los rumores de la mañana ocasionaron que los turistas se alejen". Ella vende dulces y cañas.

Paúl Bustillos, quien ayer llegó con la idea de quedarse el fin de semana en Baños, salió con sus dos pequeños hijos. "Dicen que todo está normal, pero por precaución mejor nos vamos".

Hasta la tarde de ayer, los 15 hoteles que operan en la ciudad aún no tenían una evaluación de las reservaciones canceladas.

En la tarde, igualmente, según la AFP, la Secretaría de Riesgos confirmó que hubo evacuaciones en varios poblados. "Hasta el momento la situación está controlada, se han evacuado de 400 a 500 familias", declaró Felipe Bazán, coordinador del organismo.

La organización

- **Las actividades** escolares en Baños se desarrollaron a medias ayer. Algunos centros educativos prefirieron que los niños se retiraran a sus domicilios.
- **El Centro de** Operaciones Emergentes Baños (COE) analizará el fin de semana si el lunes se suspenden las clases.
- **El COE de Baños aclaró que** la ciudad cuenta con un Sistema de Alerta Temprano y contacto permanente con el Observatorio del volcán, en Guadalupe.
- **Se recomendó que** en la familia se mantuviera una mochila de evacuación. Esto en caso de presentarse una emergencia.

Temor en Penipe p… la ceniza del volcán…

Édison Serrano / EL C…

La evacuación de los moradores. La gente de Cusúa (foto… Penipe abandonó sus casas voluntariamente por precauci…

CHIMBORAZO

Modesto Moreta. Redactor

La explosión que se registró en el volcán Tungurahua, a las 08:47 de ayer, asustó a Luis Valdivieso. Él vive en el pueblo de Chonglontús, a 12 kilómetros del cantón Penipe, en la provincia del Chimborazo.

Los vidrios de su casa se quebraron. "Salí para ver qué pasaba. Miré al volcán que arrojaba una gran columna de ceniza".

Enseguida llamó a sus hijos Édison y Alfredo para trasladar a las 35 reses que pastaban en las faldas del volcán. Los Valdivieso caminaron una hora y media para llegar al lugar.

Juntaron a los animales y bajaron rápido a la comuna El Manzano. Allí alquilaron dos camionetas para enviar las reses a la comuna El Guzo (Penipe) y la parroquia San Andrés (Guano).

"Hay que cuidar los animalitos. Es lo único que tenemos.

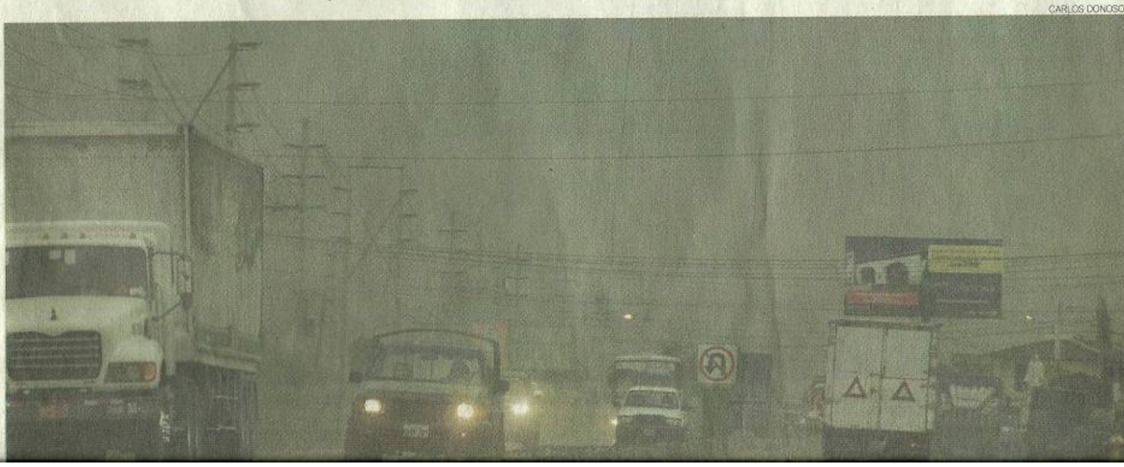
ban reportes del Institut… sico sobre el volcán.

"Tenemos la disposi… que si hay un cambio d… iniciar con la evacuació… cionó uno de los militare… quiso dar su nombre.

Miguel Mazón, vecino… la, otro pueblo de Pen… mentó que los flujos pi… cos, una mezcla de gas, … rocas, bajaron por las … das. "Por poco llegan al… La gente evacuó al cent… nipe. Allá tiene sus casa…

El gobernador y pr… del Comité de Operac… Emergencia (COE) de C… razo, Carlos Castro, co… una reunión a los repres… de la Policía, Brigada G… y a los delegados provin… los ministerios de Ed… Salud, Vivienda y otros. … realizó en la tarde en el… pio de Penipe.

Allí analizaron el infor… tido por el Instituto Ge… en base a este decidiero…



SÁBADO
29 de mayo del 2010
SANTIAGO DE GUAYAQUIL
ECUADOR
www.eluniverso.com
PRIMERA EDICIÓN

EL UNIVERSO

5 SECCIONES > 70 PÁGINAS > AÑO 89 > NÚMERO 256 — EL MAYOR DIARIO NACIONAL — PVP FINAL

Manto de ceniza llegó del Tungurahua a Guayaquil

CARLOS DONOSO

Opinión

Una medida que favorece la producción nacional

a introducir mejoras en el diseño y producción del calzado fue la decisión del Gobierno de controlar el ingreso de calzado del exterior, con lo cual se obligó a los ciudadanos a consumir la producción nacional.

En ciertas fábricas, se habla de un crecimiento de la producción de entre el 15% y el 25% debido a la creciente demanda.

La medida del Gobierno tuvo otros efectos positivos en el aumento de empleos, tanto directos como indirectos. Una conocida fábrica menciona, por ejemplo, la creación de unas 200 plazas de trabajo, muy bueno en tiempos en que el desempleo ha aumentado.

Los fabricantes nacionales mencionan que, como reciprocidad al Gobierno, que impulsó su trabajo, han privilegiado el mercado nacional sobre el de exportación.

Las perspectivas para este año son excelentes. Hablan de un aumento de la producción de hasta el 30%, para lo cual también han debido aumentar la inversión.

En Gualaceo, cantón de la provincia del Azuay, por ejemplo, la producción del calzado, en su mayor parte artesanal, ha dinamizado a esa comunidad incrementado también los puestos de trabajo no solo para quienes confeccionan, sino para quienes se dedican a su comercialización.

La presencia de compradores, sobre todo en los fines de semana, es

hoy

Sábado
29 de mayo de 2010
SEGUNDA EDICIÓN

Cotización: 1 euro = 1,22 dól

ERUPCIÓN DE VOLCÁN OBLIGA A EVACUAR »P-6 , 7 Y 10

El Tungurahua cubre de ceniza a Guayaquil

Una columna de ceniza de 10 kilómetros que expulsó el coloso llegó hasta Guayaquil. El aeropuerto fue cerrado y las actividades educativas fueron suspendidas. Poblaciones aledañas al volcán fueron evacuada

3 CUADERNO.1 EL COMERCIO Sábado 29 de mayo del 2010

ACTUALIDAD

ERUPCIÓN DEL TUNGURAHUA

Geofísico: El volcán estaba muy tranquil

QUITO El equipo de monitoreo del Instituto Geofísico de la Escuela Politécnica Nacional reportó que la primera explosión del Tungurahua fue a las 08:47 de ayer. Según Hugo Yepes, en esta ocasión la erupción no estuvo prece de emisiones de ceniza, explosiones de gases ni bramidos del volcán.

2 ACTUALIDAD EL UNIVERSO Sábado 29 de mayo del 2010

El Tungurahua retomó erupción con fuerza y afectó a 5 provincia

Poblados cercanos al coloso, evacuados. Se suspenden vuelos y clases en las zonas afectadas.

WILSON PINTO
BAÑOS, TUNGURAHUA

Un fuerte cañonazo registrado a las 08:47 de ayer en el volcán Tungurahua originó la emisión de grandes de cantidades de ceniza que horas después provocó la alerta en las provincias de Guayas, Tungurahua, Chimborazo, Bolívar y Los Ríos.

El evento de ayer, según vulcanólogos del Instituto Geofísico de la Politécnica Nacional, es uno de las tres más fuertes de todo el proceso eruptivo que empezó en 1999. Los otros ocurrieron en el 2006 y 2008.

La nube de polvo volcánico, que alcanzó los 10 kilómetros de altura y dirección suroccidente, alteró las actividades en las referidas provincias con sus-

EL UNIVERSO
Sábado 29 de mayo del 2010 **ACTUALIDAD**

MARTÍN HERRERA

Las mascarillas se comercializaron entre 0,25 y 0,50 centavos, en la avenida Carlos Julio Arosemena.

FRANCISCO BRAVO

Pasadas las 12:00 así estaba la avenida de las Américas, frente al aeropuerto José Joaquín de Olmedo.

RONNY ZA

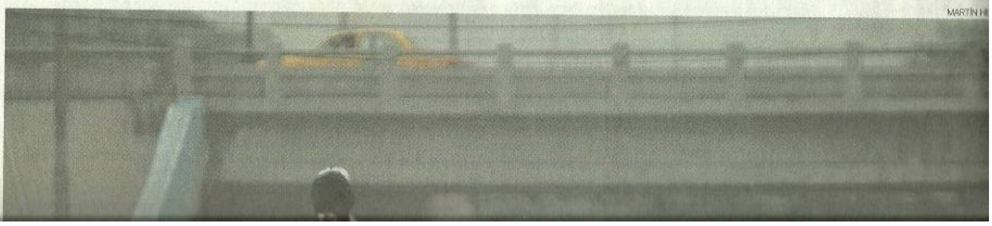
En la avenida Nueve de Octubre, algunas personas se proteg con mascarillas.

Ceniza alteró la jornada en muchas zonas de Guayaquil

Los ciudadanos buscaron protegerse con mascarillas y pañuelos. Las clases fueron suspendidas.

De un momento a otro, cientos de guayaquileños empezaron a usar pañuelos y mascarillas

MARTÍN H



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APPENDIX 5 ETHICS APPROVAL NUMBERS

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Co-Authorship Form

This form is to accompany the submission of any PhD thesis that contains research reported in co-authored work that has been published, accepted for publication, or submitted for publication. A copy of this form should be included for each co-authored work that is included in the PhD thesis.

Appendix 2: Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala

Published in: GNS Science Report
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Mr. Wardman is the first author, while Ms. Victoria Sword-Daniels, Dr. Carol Stewart and Dr. Thomas Wilson are co-authors. Mr. Wardman, Ms. Sword-Daniels and Dr. Stewart contributed equally to the writing process and Dr. Wilson provided useful discussion and review of the manuscript.

Certification by Co-authors:
If there is more than one co-author then a single co-author can sign on behalf of all.

The undersigned certifies that:
- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work;
- In cases where the PhD candidate was the lead author of the co-authored work he or she wrote the text.

Name: *Thomas Wilson* Signature: [signature] Date: *28 March 2013*

Appendix 2

Impact assessment of the May 2010 eruption of Pacaya volcano, Guatemala

GNS Science Report (2012/09)

June 2012

ISSN 1177-2425
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By Johnny Wardman, Victoria Sword-Daniels, Carol Stewart, and Thomas Wilson

96 pages

Infrastructure impacts, management and adaptations to eruptions at Volcán Tungurahua, Ecuador, 1999-2010

V. Sword-Daniels
C. Stewart
D. Johnston
J. Wardman
T. Wilson
T. Rossetto

GNS Science Report 2011/24
January 2011

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ACRONYMS

CNEE	Comision Nacional de Energia Electrica is the national electricity commission that supervises the energy wholesale market in Guatemala.
INDE	Instituto Nacional De Electrificacion is the self-financing government entity in charge of operating and maintaining the power transmission network (>69 kV) throughout Guatemala.
ETCEE	Empresa de Transporte y Control de Energia Electrica is a subsidiary company of INDE that manages operates and maintains the electricity transmission (>69 kV) and distribution (<69 kV) in terms of quality prescribed by the General Electricity Law.
EEGSA	Empresa Electrica de Guatemala is a distribution supply (<69 kV) company that provides electricity to the departments of Guatemala, Sacatepeguez and Escuintla.
CONAGUA	Comision Nacional del Agua is the national water commission.
EMPAGUA	Empresa Municipal de Agua is the municipal water company serving 85 percent of Guatemala City's water users.
DGAC	The Direccion General de Aeronautica Civil is the institution responsible for regulating, managing, facilitating and monitoring the provision of airport services and air navigation, in accordance with current legislation and international agreements ratified by the State of Guatemala.
INSIVUMEH	Instituto Nacional de Sismologia, Vulcanologia, Meterologia, e Hidrologia (English translation: National Institute of Seismology, Volcanology, Meteorology and Hydrology) monitors all natural hazards including volcanic activity.
CEPAL	La Comisión Económica para América Latina (English translation: Economic Commission for Latin America and the Caribbean (ECLAC)).
CONRED	Coordinadora Nacional para la Reducción de Desastres (English translation: National Disaster Reduction Coordinator) is the coordination agency within Guatemala for Disaster Risk Management.
CODRED	Department [province] level response agency (as related to CONRED).
COMRED	Municipality level response agency (as related to CONRED).
COLRED	Local level response agency (as related to CONRED).

ABSTRACT

This report summarises the field observations and interpretations of a reconnaissance trip to Guatemala in September 2010. The purpose of this trip was to investigate the impacts of the 27 May 2010 eruption of Pacaya volcano, located approximately 30 km SSW of Guatemala City. This eruption was of particular interest as it presented an opportunity to study an event with parallels to an eruption of the Auckland Volcanic Field and its consequences for the city of Auckland. A further interesting feature of this event was that a major tropical storm arrived immediately after the eruption, providing an opportunity to study the interaction between two co-occurring natural disasters.

The 27 May 2010 eruption of Pacaya volcano began shortly after 14h00. The paroxysmal phase started shortly after 19h00 and lasted approximately 45 minutes. This phase generated a plume that was directed towards the north. At Cerro Chino, 1 km from crater, large ballistic fragments (up to half a metre in length) fell, killing one news reporter, injuring many others and destroying buildings, vehicles and equipment. This took local communities and civil defence by surprise as previous tephra falls had been to the west and southwest of the crater and preliminary civil defence efforts had been focussed on those areas. Three communities located 2.5-3.5 km to north of crater were particularly badly affected by the fall of ballistic clasts. Roofs in these towns were extensively damaged by ballistic blocks and to a lesser extent by tephra accumulation. The tephra plume travelled to the north, and Guatemala City was covered in an estimated 2-3 cm of coarse basaltic tephra which local residents described as being like ‘black sand’.

The majority of the report is concerned with describing impacts of the tephra fall on Guatemala City. A prompt and efficient citywide cleanup was initiated by the city’s municipality to remove tephra from the 2100 km of roads in the capital. An estimated 11,350,000 m^3 of tephra was removed from the city’s roads and rooftops. The possibility of using the tephra for aggregate in cement production was investigated, but it was found to be too friable (low mechanical strength). It was disposed of in landfills around the city. Despite the cleanup operations, considerable quantities of tephra were washed into the city’s underground drainage network from where it was very difficult to remove. Blockages of stormwater drains led to surface flooding of the city’s road network which persisted for months afterwards. Tephra also entered the city’s many wastewater treatment plants, both by direct deposition and through sewer lines. There was no option but to clean out all these systems, an expensive and time-consuming job.

A number of accidents happened during the cleanup operations. Limited data available from hospital emergency department admission records indicates that most of these were caused by people falling from their roofs, and other heights, while cleaning up the tephra. The eruption did not cause any discernible increase in respiratory illnesses above normal wintertime levels. This is probably due to several factors: the grain size of the tephra was coarse, with no material present in very fine fractions that can penetrate into the lungs, and the eruption happened in the evening and in rainy conditions and thus most people were indoors. The eruption appeared to have minimal effect on the functioning of two of Guatemala City’s large public hospitals, other than exacerbating pre-existing drainage and flooding problems for one of them as tephra blocked downpipes, gutters, drains and sumps.

For electricity and water supplies, effects of the eruption on continuity of supply were minor, although problems were experienced. A geothermal plant close to the volcano was badly damaged by falling ballistic clasts, and had to be closed for repairs and cleaning for three

weeks. Flashover was also a problem for distribution lines. Cleaning of tephra from substations was mostly unnecessary because of the arrival of the tropical rainstorm shortly afterwards. For the city's water supplies, a large storage tank was contaminated by tephra and had to be cleaned out, and there was also abrasion damage to air-cooled motors and groundwater pumps, but generally there was little overall disruption to the continuity of supply beyond normal variations.

Probably the most significant disruption caused by the tephra fall was the closure of the international airport for five days, to allow cleanup of the runway and apron. A complication of the cleanup operation was that the tephra was extremely abrasive, and in the process of cleaning a new bituminous runway surface was destroyed and all markings on the runway and apron were removed also. A similar, though more minor problem, was reported while cleanup of the large flat roofs of one of the public hospitals was underway, when a waterproof coating was damaged by abrasion. Development of cleaning methods to minimise abrasion damage may be worth considering for future eruptions of this type.

The arrival of a major tropical storm immediately after the eruption generally added to the difficulties experienced by organisations and individuals involved in the response. The storm had a much larger and more widespread impact on the country, resulting in 160 deaths and over 168,000 people requiring evacuation, compared to two deaths (plus two more indirect deaths due to accidents while clearing tephra) and just over 3,000 people evacuated as a result of the eruption. While the heavy rains made some of the impacts of the eruption worse (in particular, it washed the tephra into underground drainage networks before the cleanup was complete, which has in turn worsened drainage problems in the city), it also dampened down the tephra, minimised the corrosive potential of the tephra by washing away its chemically active surface coating), and suppressed fires.

KEYWORDS

Guatemala, Pacaya volcano, Strombolian eruption, impact assessment, infrastructure, electricity supply, water supplies, healthcare services, cleanup, ashfall.

1.0 INTRODUCTION

The mitigation of volcanic hazards requires good knowledge of the styles of eruption that can occur, the range of hazards that can be generated and the potential impacts that these may cause. Furthering our knowledge of overseas experiences of eruption styles, impacts, monitoring, mitigation and adaptation will help New Zealand prepare for and respond to future volcanic events (Leonard et al., 2005).

This report summarises the field observations and interpretations of a reconnaissance trip to Guatemala in September 2010. The purpose of this trip was to investigate the impacts of the 27 May 2010 eruption of Pacaya volcano, located approximately 30 km SSW of Guatemala City. The eruption deposited 2-3 cm of tephra on Guatemala City (population 1.1 million, although the greater Metropolitan Region of Guatemala (centred on Guatemala City) has a much larger population of 3.6 million (Cerezo, 2003)). This presented our research group with a good opportunity to investigate the impacts of a low explosivity, basaltic eruption close to a major urban environment.

1.1 Personnel

Fieldwork in Guatemala was carried out between 18-26 September 2010 by a team from the University of Canterbury, Christchurch, New Zealand, and University College London. For a complete trip itinerary, refer to Appendix 1.

The field team consisted of: Johnny Wardman (doctoral student, University of Canterbury), Victoria Sword-Daniels (doctoral student, University College London), Carol Stewart (research associate, University of Canterbury) and Fiona Woods (translation support). The wider team that supports this work also includes: Tom Wilson (University of Canterbury), David Johnston (Massey University/GNS Science), and Tiziana Rossetto (University College London).

1.2 Aims of study

The research group was particularly interested in:

- Impacts on essential infrastructure (e.g. electrical supply and generation networks, water supplies, wastewater systems and transport and communication networks);
- Impacts on healthcare service provision;
- Impacts on hospital facilities and clinics;
- Activation of hospital emergency management plans;
- Socio-economic impacts, such as stresses and disruption due to evacuation;
- Impacts to agriculture, including livestock evacuation;
- Hazards caused by remobilisation of tephra deposits;
- Assessment of evacuation planning during a volcanic crisis;
- Factors affecting evacuation of communities;
- The role of local, central government and NGOs in a volcanic crisis.

Our aim on this trip was to gather as much information on these topics as possible within the constraints of a very brief field visit.

1.3 Research methodologies

Research methods for the fieldwork included: field observation, field-testing, meetings, and semi-structured interviews.

Prior to our arrival in Guatemala, we identified relevant agencies and attempted to contact them to arrange interviews. This proved difficult and most interviews were organised in the course of our visit, and by using referrals from interviewees.

Meetings and semi-structured interviews were conducted at infrastructure offices and facilities in affected areas, using a translator to conduct the interviews in Spanish. Ethical approval for the interviews was granted from the University of Canterbury and University College London prior to leaving (Appendix 4). The interviewees were mainly managers, directors and operating professionals for each infrastructure system. The sectors that were investigated during fieldwork were: power, water and wastewater, airport, healthcare, municipality, agriculture and emergency management at the national level.

The interviews followed several prompt questions which were used to steer the conversation, and touched upon the main topics of interest for research including: the general impacts of volcanic tephra fall on the sector; actions taken in response to tephra fall; tephra ingress and any associated problems; emergency management plans; interrelated power, water and access impacts on the sectors.

Interviews were semi-structured in nature to allow for freer exploration and discussion around the various topics that were touched upon in conversation. However, conducting interviews through a translator meant that some questions needed to be phrased in a proactive manner, to maintain the focus of the interview and to avoid misinterpretations as a result of translation. In general the interviewee was asked to speak freely following a prompt question and the translator would summarise the comments when they had finished. This allowed the researcher to have some level of continued exploration of some of the aspects mentioned in dialogue by the participant. But detailed explanations at the time were not deemed appropriate in the interview, in order to maintain the interest of the interviewee and to reduce the interview time.

Interviews were recorded by dictaphone and consent forms were signed by the interviewee(s) at the time of interview, in accordance with ethical guidelines. A copy of the inventory of audio recordings and other data collected during fieldwork can be found in Appendix 2.

A total of twelve interviews were conducted within the fieldwork period of two weeks, which varied in length from 27 to 110 minutes. All sectors had a 100% uptake rate when contacted for interview.

Interviews were supplemented by the author's own field observations, and by informal conversations with local members of the population.

1.4 Characteristics of study areas

1.4.1 National overview

The Republic of Guatemala is located on the Central American Isthmus and is bordered by Mexico, El Salvador, Honduras and Belize, as well as the Pacific Ocean and the Caribbean Sea (Figure 1.1). It has an area of 108,890 km^2 and a current population of approximately 14.4 million (Population Reference Bureau website, accessed March 2011). Its estimated population growth rate of approximately 2% is greater than the current global average of approximately 1% per annum (CIA World Factbook, accessed March 2011). Administratively, Guatemala is divided into eight regions, 22 departments and 331 municipalities.

Figure 1.1 Map of Guatemala (source: http://www.worldmapnow.com)

According to a United Nations series of reports on human settlements (Cerezo, 2003); in 1999 Guatemala ranked 117 out of a total of 174 countries in 1999, with a per capita GDP of US$1,690 compared to the average GDP for Latin America and the Caribbean of $US4,127. Income distribution was reported to be very uneven, and approximately 70 percent of the population then lived on less than $US2 per day. More recent estimates of GDP provided by the International Monetary Fund, shown in Table 1.1, indicate that Guatemala still languishes well below the global average per capita income. Poverty is more strongly associated with rural than with urban populations (Cerezo, 2003).

Table 1.1 Recent estimates of per capita GDP for Guatemala, New Zealand and a world average (data: International Monetary Fund).

	2009 (US$)	2010 (US$)	2011 (US$)
Guatemala	2,689	2,888	3,154
World	11,064	11,342	11,822
New Zealand	27,284	32,145	34,701

Geographically, there are three main regions in Guatemala: the Pacific coastal plains, the mountainous interior dominated by the Sierra Madre, which forms the main drainage divide between river systems draining south towards the Pacific Ocean and north and east towards the Caribbean (Figure 1.1). There are extensive lowlands to the north, in the Petén region. The tectonic setting is described further in Section 2.1.

1.4.2 Guatemala City

Guatemala City is located in the southern central highlands. It is the capital of Guatemala and its largest city. Its current population is approximately 1.1 million. However, the greater Metropolitan Region, centred on the city, has a much larger population of 3.7 million (approximately 26% of the total population of Guatemala). Guatemala City is the largest city in Central America (this excludes Mexico), and is the centre of political, economic and industrial power in the country. It is also the main point of entry into the country, with La Aurora International Airport located in the city (figure 1.2).

The city was founded by the Spanish in 1776, after a major earthquake in 1773 destroyed much of the old capital city of Antigua. At the beginning of the 20th century, the city had about 100,000 inhabitants. Since then, there have been several waves of migration from rural areas. In 1954, the state put an end to an agrarian reform programme, prompting an acceleration in migration such that the city's population grew from 285,000 inhabitants in 1950 to 573,000 in 1964. Many immigrant families were forced to live on unoccupied urban land which produced new slums (or 'precarious urban settlements'). In 1976, a magnitude 7.5 earthquake centred 160 km northeast of Guatemala City led to a death toll of over 23,000 and caused severe damage to housing and infrastructure across the whole country, leaving over a million people homeless. This caused a further exodus from rural areas. Armed conflict and a civil war between 1960-1996 also caused further waves of migration of displaced people.

In the 2003 United Nations Report on Human Settlement, Cerezo (2003), in his case study report on Guatemala City, said that:

At the beginning of the 21st century, the city is characterised by a large horizontal expansion, with peripheral commercial subcentres, an inefficient public transport system, a proliferation of precarious settlements, a free market economy and a decrease in state attention to housing needs. Of its 2.5 million inhabitants, approximately a third live in precarious settlements.

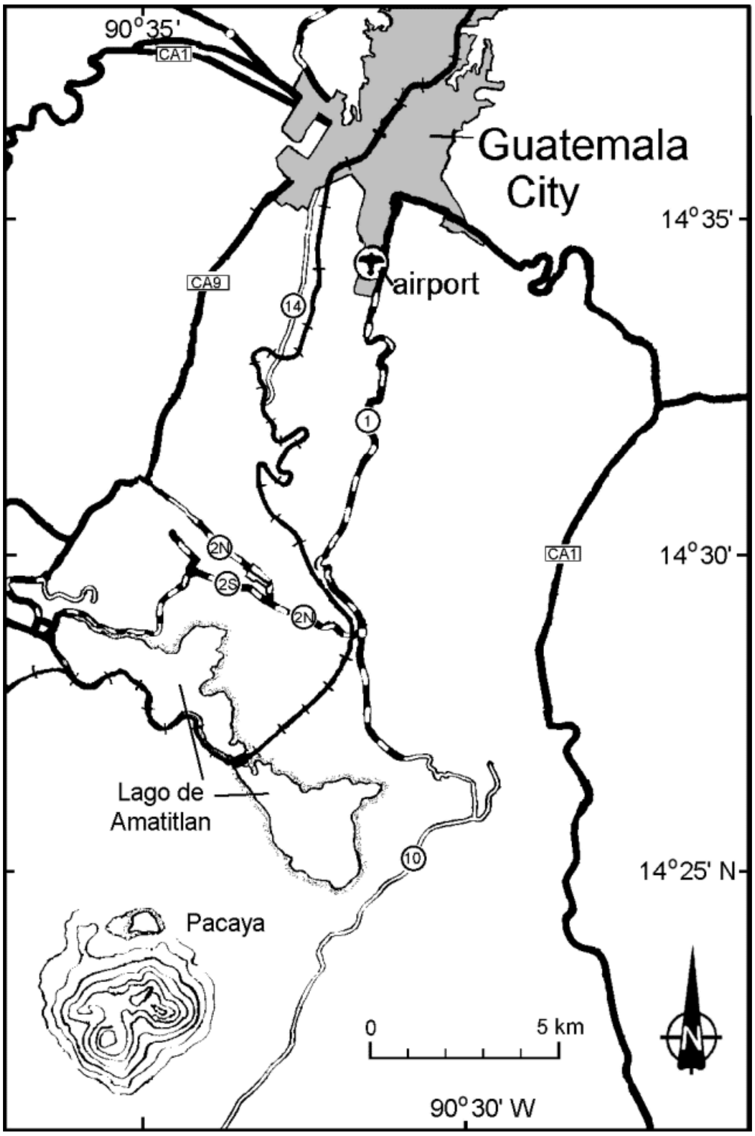


Figure 1.2 Location of Guatemala City relative to Pacaya volcano (source: Smithsonian Institute Global Volcanism Program).

1.4.3 Settlements around Pacaya volcano

According to Matias Gomez (2009), approximately 9000 people live in communities close to Pacaya volcano, within 5 km of the active cone (Table 1.2, Figure 1.3). The following population data on communities surrounding Pacaya is courtesy of Rudiger Escobar Wolf (Escobar Wolf, 2011). Administratively, all are in Escuintla department, and within the municipality of San Vicente Pacaya.

Table 1.2 Communities surrounding Pacaya (2010 projections of population data).

Settlement	Total population
San Vicente Pacaya	7990
El Cedro	1020
San Francisco de Sales	820
Calderas	960
Mesillas Altas y Bajas	2710
Los Rios	370
El Patrocinio	1620
El Rodeo	150
El Caracol	10

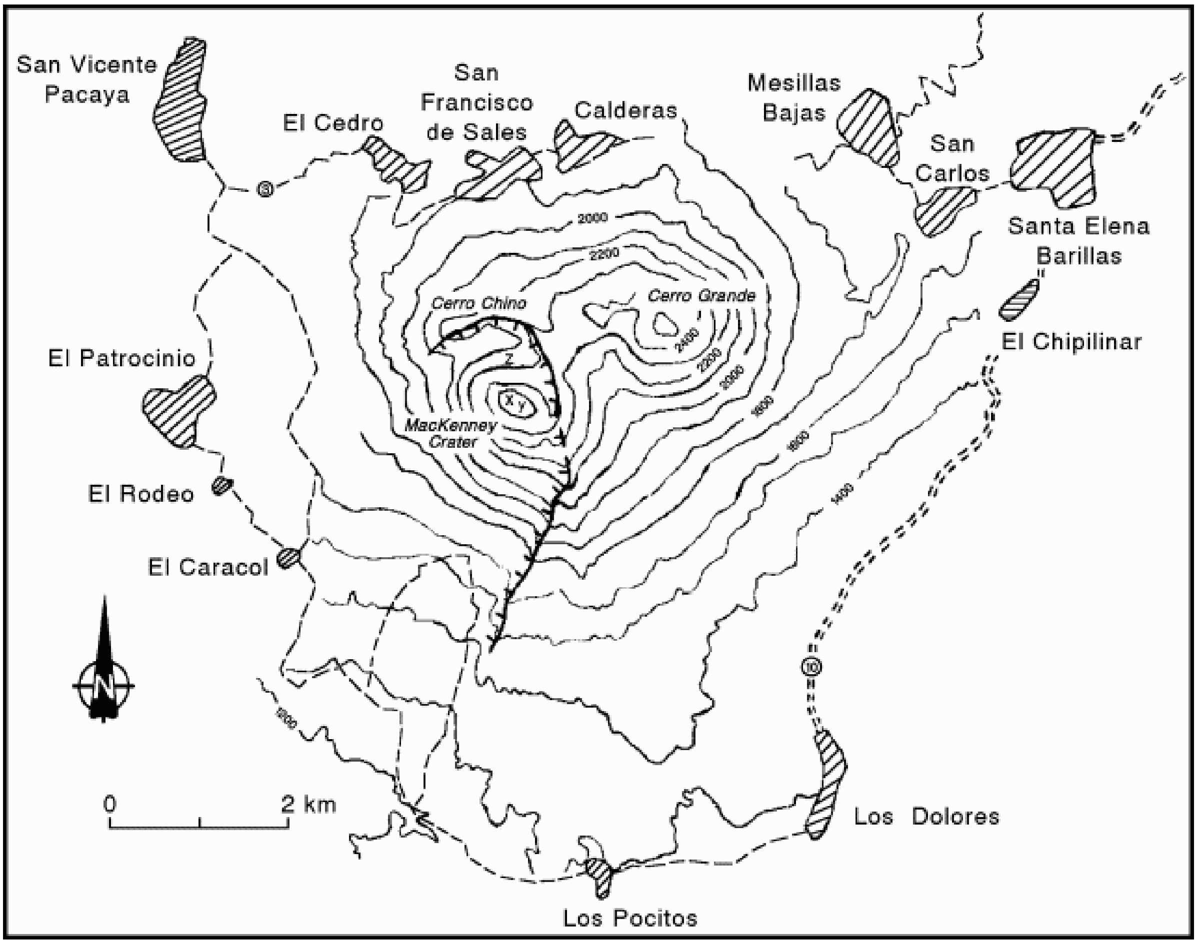


Figure 1.3 Location of Pacaya volcano and nearby settlements. The hachured line indicates the caldera rim. The contour interval is 100 m (source: Smithsonian Institute Global Volcanism Program).

2.0 VOLCANIC HAZARDS IN GUATEMALA

2.1 Overview of volcanic hazards in Guatemala

Guatemala lies between the North American, Cocos and Caribbean tectonic plates. The Cocos plate is subducting beneath the Caribbean plate along the Middle America Trench, to the west of the Guatemalan mainland (Spence and Person, 1976). This has produced a NW-SE oriented chain of volcanoes in western Guatemala. There are 22 volcanoes of Holocene age (<0.1 m.a.) listed for Guatemala on the Smithsonian Institute website (SI, 2010). Major volcanoes are shown in Figure 2.1. The plate boundary between the North American and Caribbean plates is a transform boundary (left-lateral), and runs approximately E-W through the centre of Guatemala, forming a triple junction with the Cocos plate to the west of the Guatemalan mainland.

The tectonic setting of Guatemala renders it at risk from both earthquake and volcanic hazards (Table 2.1). The volcanic hazards vary in accordance with the volcano type and magma composition. Guatemala has stratovolcanoes, lava domes and complex volcanoes (SI, 2010). Large caldera-forming eruptions are highly explosive but infrequent. More frequent eruptions occur from stratovolcanoes with intermediate magma compositions that are associated with the following hazards: pyroclastic flows, explosions, tephra falls, lava flows and lahars.

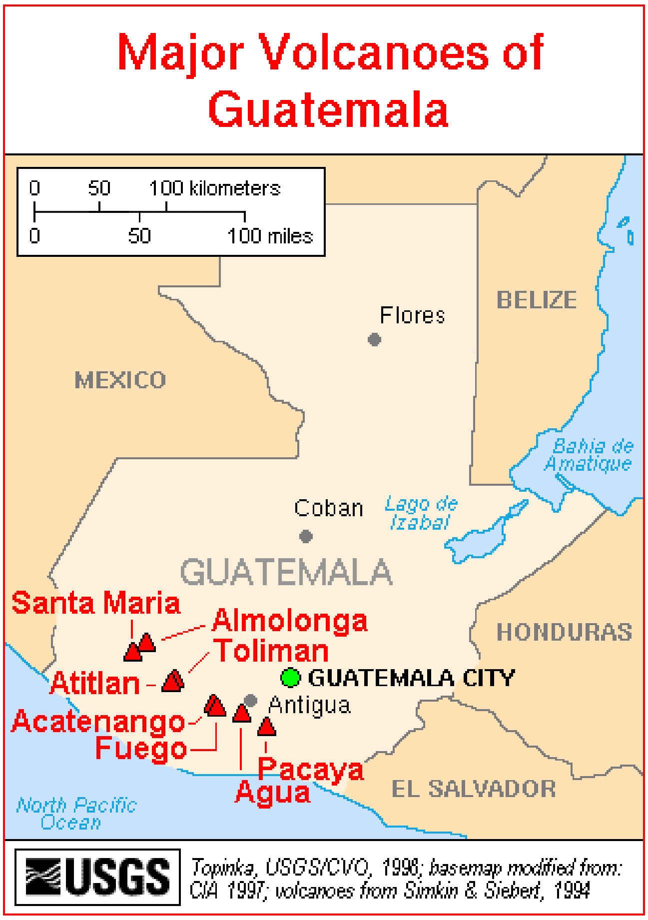


Figure 2.1 Location of major volcanoes of Guatemala (source: USGS).

Table 2.1 Eruption frequencies for selected countries (after Wilson et al. 2009a).

Selected countries	Population (2008)[1] (million)	Average eruption frequency	
		VEI[2]0-3	VEI 4-7
Indonesia	239.9	6 months	15 years
Iceland	0.3	6 years 10 months	43 years
Japan	127.7	7 months	44 years
Guatemala	14.4	4 years 9 months	53 years
Philippines	90.5	1 year 4 months	59 Years
Papua New Guinea	6.5	8 months	81 years
Alaska, Kamchatka, Kuril Is	1.1	5 months	100 years
Ecuador	13.8	2 years 5 months	102 years
Canada, Lower 48 states USA	335.8	1 year 6 months	143 years
Italy	59.9	5 years	215 years
Colombia	44.4	6 years 6 months	304 years
Mexico	107.7	7 years 6 months	375 years
New Zealand	4.3	11 months	394 years
Chile	16.8	1 year 4 months	554 years
Nicaragua	5.7	1 year 2 months	806 years
Peru	27.9	14 years 2 months	832 years

[1] 2008 World Population Data Sheet, Population Reference Bureau
[2] The Volcanic Explosivity Index (VEI) is a classification scheme for volcanic eruptions, ranging from VEI 0-8, with VEI 0 the least explosive (Newhall and Self, 1982).

2.2 Pacaya volcano: eruption history and volcanic hazards

Pacaya volcano is a large volcanic complex located approximately 30 km south of Guatemala City (Figures 2.1, 2.2, 2.3). The Pacaya volcanic complex comprises an ancestral andesitic Pacaya stratovolcano, rhyodacite and andesite domes, and the modern Pacaya basaltic composite volcano (Kitamura and Matias, 1995). Pacaya volcano collapsed around 1100 years ago, producing a debris avalanche deposit that reaches to the Pacific coast, and forming a horseshoe-shaped caldera which is open to the southwest (Conway et al., 1992). The modern Pacaya volcano is MacKenney Cone, 2552 m in height (Figure 2.4). This cone is around 800 years old and formed within the caldera. A smaller parasitic scoria cone called Cerro Chino also formed and lies on the northern edge of the caldera. It was last active in the 1800s (SI, 2010).

In historic times, many eruptions of Pacaya volcano have been recorded (Table 2.2). The first recorded eruption was in 1565; heavy tephra fall was recorded in Antigua (Kitamura and Matias, 1995). The next recorded unrest commenced in 1651 and unrest continued intermittently until about 1700. In 1775, another strong eruption caused tephra fall and darkness in Antigua, and was thought to occur at the Cerro Chino crater. There were further small eruptions in the mid-19th century.

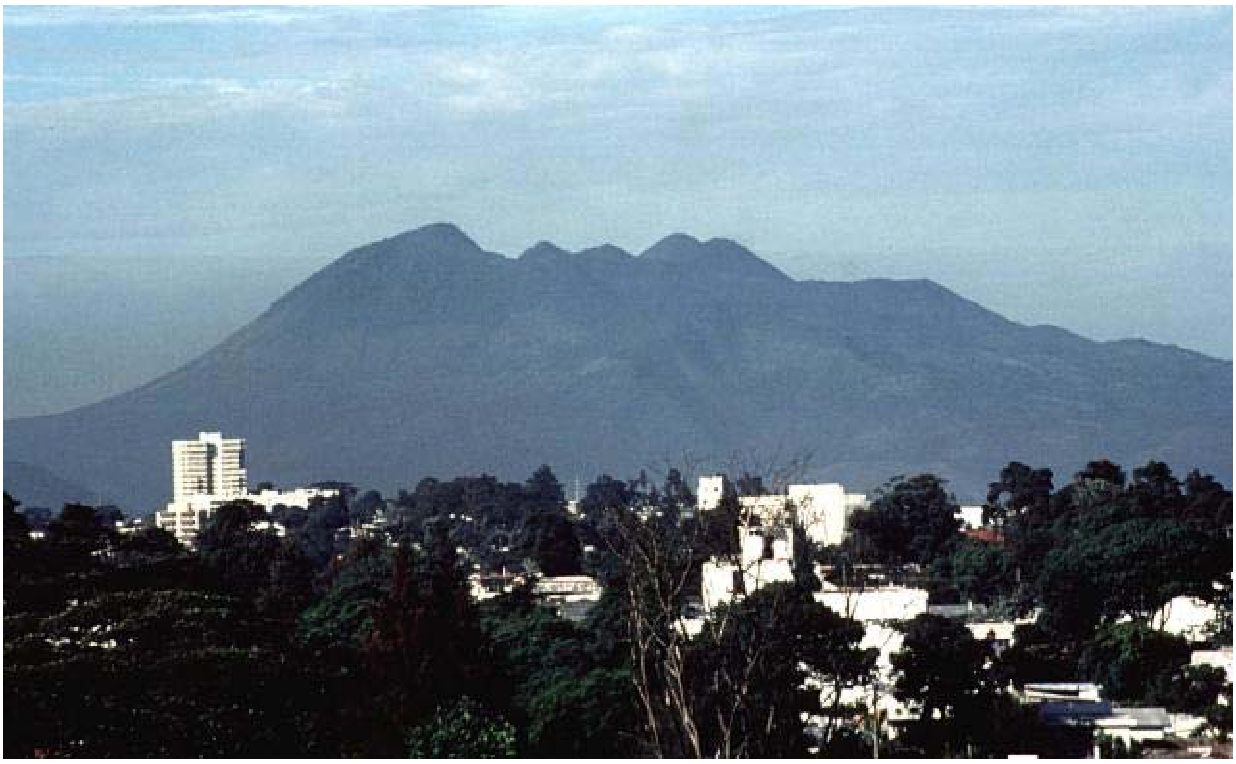


Figure 2.2 Pacaya volcano seen from Guatemala City. MacKenney Cone is the second from the right, with Cerro Chino immediately to its right (photo: Smithsonian Institute).

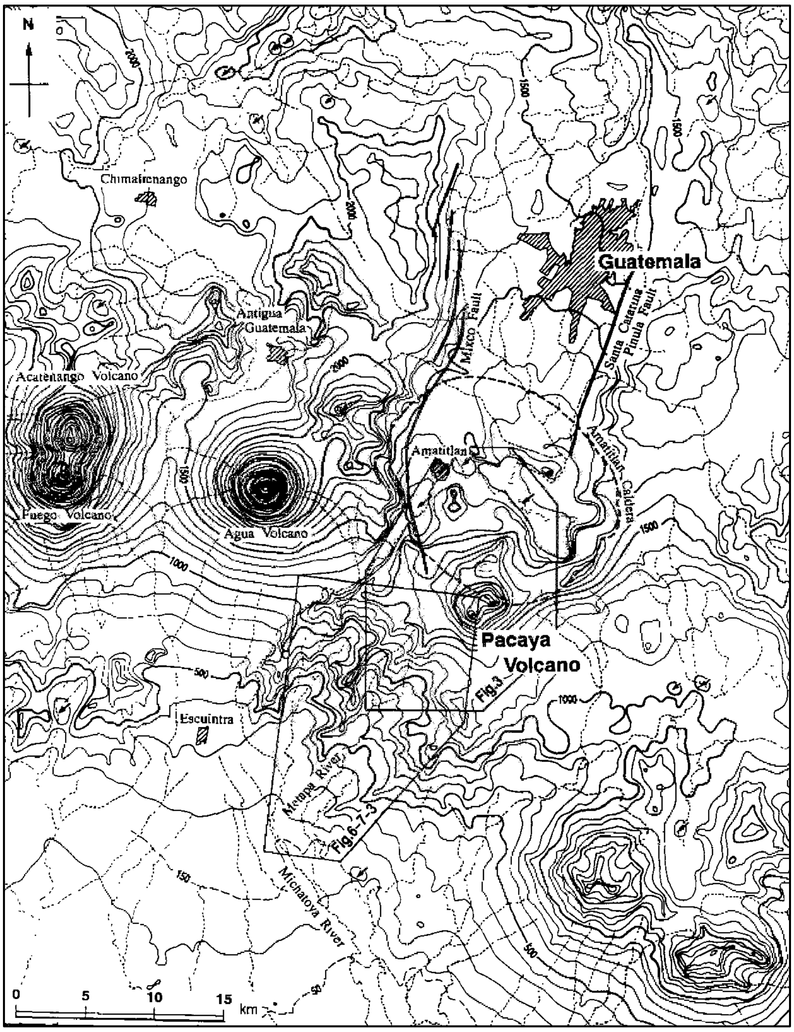


Figure 2.3 Topographic map of Fuego, Agua and Pacaya volcanoes (source: Smithsonian Institute Global Volcanism Program).

Figure 2.4 MacKenney Cone in 2006 (photo: Gustavo Chigna, INSIVUMEH).

From 1860 to 1961, Pacaya volcano was in repose (Conway et al., 1992). On 10 March 1961, the volcano erupted without warning and it has been intermittently active since then. Recent activity has all originated from MacKenney Cone, and has been characterised by continued strombolian activity and lava flows, some as large as 10^6 m^3. During Strombolian eruptions, incandescent bombs are typically ejected hundreds of metres into the air, and small volume a'a lava flows stream down from the summit. The historical and recent activity of Pacaya volcano is discussed in further detail in Table 2.2.

The principal volcanic hazards at Pacaya volcano include lava flows, tephra fall, ballistic blocks and to a lesser extent pyroclastic flows and debris avalanches (Conway et al., 1992). Approximately 9000 people live within 5 km of the active cone, in the villages of El Caracol, El Rodeo and El Patrocino on the southern side, and San Francisco de Sales and San José Calderas on the northern side. The volcano and its surroundings were declared a national park in 1963 and it is a source of income for the local population through tourist ventures. There have been 10 evacuations of the population from these towns since 1987 (Matias Gomez, 2009).

Until 2006, the main hazard for people living on the slopes of Pacaya volcano has been tephra fall and ballistic bombs. Lava flows and pyroclastic flows have mostly been confined by topographic barriers formed by an old collapse scarp, and have thus been restricted to the slopes of MacKenney Cone. However, in 2006, accumulation of lava on the northern side overtopped the topographic barrier such that new lava flows on this side could threaten the resident population. The village of San Francisco de Sales is particularly at risk from lava flows as it is sited only 3 km from the crater, on the northern side.

Table 2.2 Historical and recent activity of Pacaya volcano. Lava flows and intermittent activity have occurred throughout the period 1961-2010 and have not been delineated as separate events. (Sources: Kitamura and Matias, 1995; Matias Gomez, 2009; Conway et al., 1992; Smithsonian Institute Global Volcanism Program; Gomez et al., 2012).

Date	Event
1565	VEI 3 explosive eruption, heavy tephra fall reported in Antigua, damage to property, lava flows. Probably originated from Cerro Chino cone.
1623	VEI 3 explosive eruption, damage to property.
1651	VEI 2 explosive eruption, tephra fall and lava flows.
1655	VEI 2 explosive eruption.
1664	VEI 3 explosive eruption.
1668	VEI 2 explosive eruption.
1671	VEI 2 explosive eruption.
1674	VEI 2 explosive eruption.
1678	VEI 2 explosive eruption.
1687	VEI 2 explosive eruption.
1690	VEI 2? explosive eruption.
1693	VEI 2? explosive eruption.
1699	VEI 2? explosive eruption.
1775	VEI 3 explosive eruption from Cerro Chino cone. Caused tephra fall and darkness for several days in Antigua, and a basalt lava flow that travelled 6 km to the southwest.

Date	Event
1805	VEI 2 explosive eruption.
1846	VEI 2 explosive eruption from Cerro Chino cone.
1885	VEI 2 explosive eruption.
1961	10 March 1961: VEI 2 explosive eruption. Damage to property, lava flows.
1964	VEI 3 explosive eruption from MacKenney Cone. Damage to property, pyroclastic flows, lava flows, lava lake, evacuation.
1987	January: 'unusually explosive eruptions destroyed 63 homes and forced 3000 people to evacuate'. A shower of bombs and cinders destroyed a forest 1 km to north of MacKenney Cone. June: Large explosive eruption destroyed top of MacKenney Cone, tephra fall 8-10 cm thick up to 5 km SW of Pacaya volcano. Lava flows caused villages of El Caracol, El Rodeo and El Patrocino S-SW of the cone to be evacuated.
1991	June-August: pyroclastic flow-forming eruptions threatened nearby communities, leaving 2000 people homeless, 1-4 cm tephra fall reported more than 20 km west of the cone, with >1 cm deposited on Escuintla City. An estimated tephra volume of 1-8 x 10^7 m^3 implies VEI 2-3.
1996	November: eruption that distributed tephra to southwest, with approximately 0.5 cm deposited on Escuintla City. An estimated tephra volume of 2-6 x 10^6 m^3 implies VEI 1-2.
1997	May: eruption distributed tephra to NNE, depositing 1-5 mm tephra on Guatemala City. A smaller plume also travelled to the SW. The estimated tephra volume was 2-3 x 106, or VEI 1.
2000	The build-up to this eruption started in December 1999 with Strombolian activity that built a 50 m high cinder cone. In January, there were lava flows to the north, southwest and south. On 16 January, there was spectacular fire fountaining to 800 m above the crater, which was seen from Guatemala City. Tephrafall to the south of the vent (up to 30 cm tephra) caused the evacuation of 1000 people, and the hazard to airspace caused the closure of La Aurora international airport. There was a further eruption on 29 February with a tephra column 2 km high and tephra fall on the towns of Escuintla and Siquinala. The National Disaster network declared a Red Alert and surrounding towns were evacuated.
2001	VEI 1 explosive eruption.
2002	VEI 1 explosive eruption.
2004	VEI 1 explosive eruption, lava flows.
2006	March-April: lava flows from MacKenney Cone to the north. Accumulation of lava next to scarp on northern side implies that the scarp wall no longer confines future lava flows down north flank.
2010	27 May: Largest eruption since 1964. A plume 3 km high was produced, along with a directed blast to the north. Ballistic blocks fell up to 6-7 km from the vent. The eruption plume travelled to the north and northeast, depositing 2-3 cm coarse tephra on Guatemala City.

Michigan Tech (2010) have produced a detailed map of the eruptions of Pacaya volcano from 1961-2010, including information about the dates and locations of lava flows. This is included as Figure 2.5.

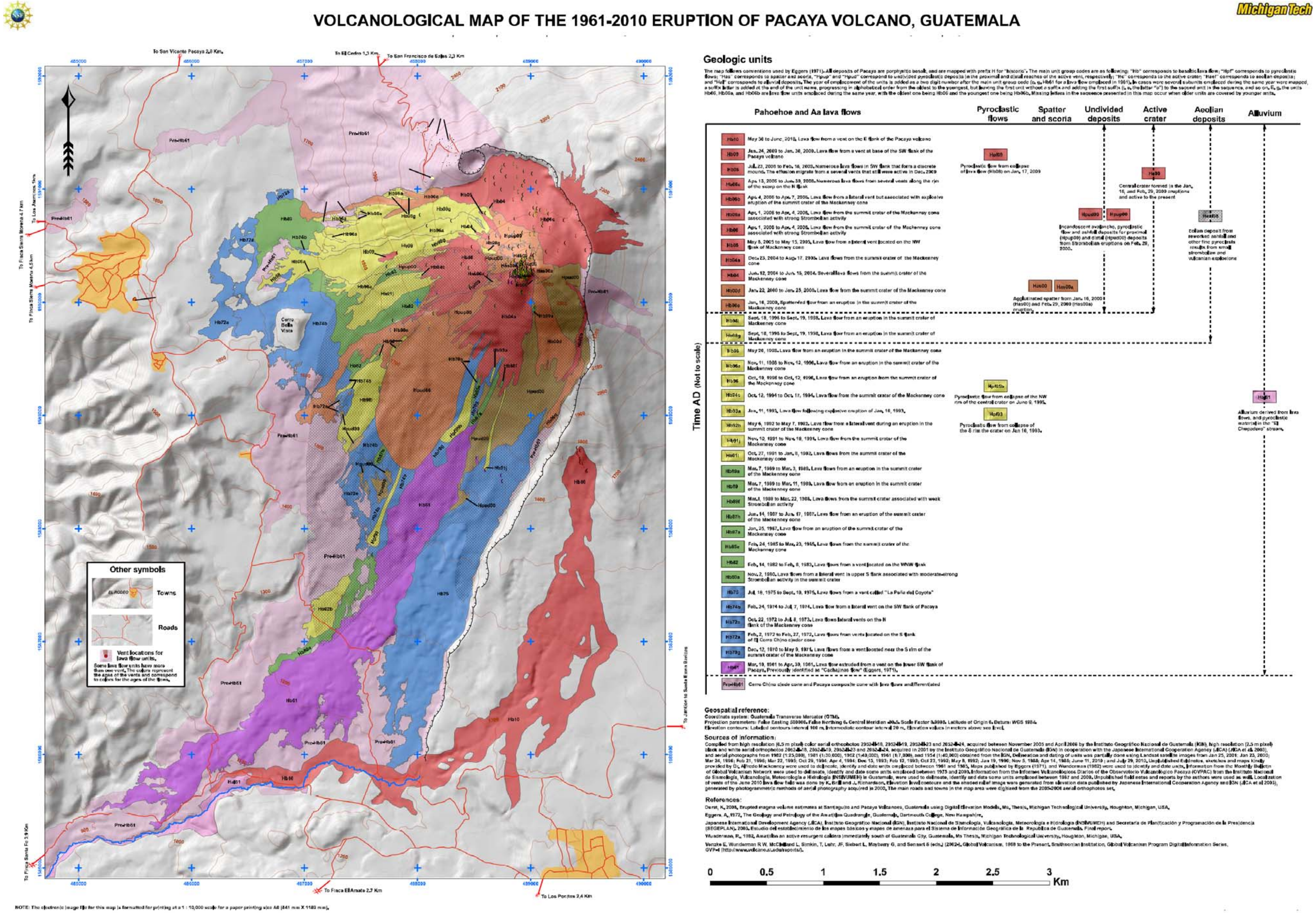


Figure 2.5 Volcanological map of the Pacaya volcano eruptions from 1961-2010 (source: Gomez, 2012).

2.3 Chronology of May 2010 eruption of Pacaya volcano

The following summary is derived from the Smithsonian Institute's Global Volcanism Program weekly reports and from a report prepared by Instituto Nacional de Sismologia, Vulcanologia, Meterologia, e Hidrologia (INSIVUMEH) or the National Institute of Seismology, Volcanology, Meteorology and Hydrology (Report Erupción Pacaya volcano 1402-11). Note that further information on civil defence aspects of the eruption is summarised in Table 5.2 of this report.

The eruption that commenced on 27 May 2010 was the largest since 1964. The current activity period is considered to have started in 2006, when a series of radial cracks formed around the active cone which may have led to an increased level of effusive activity on the north, west and south flanks.

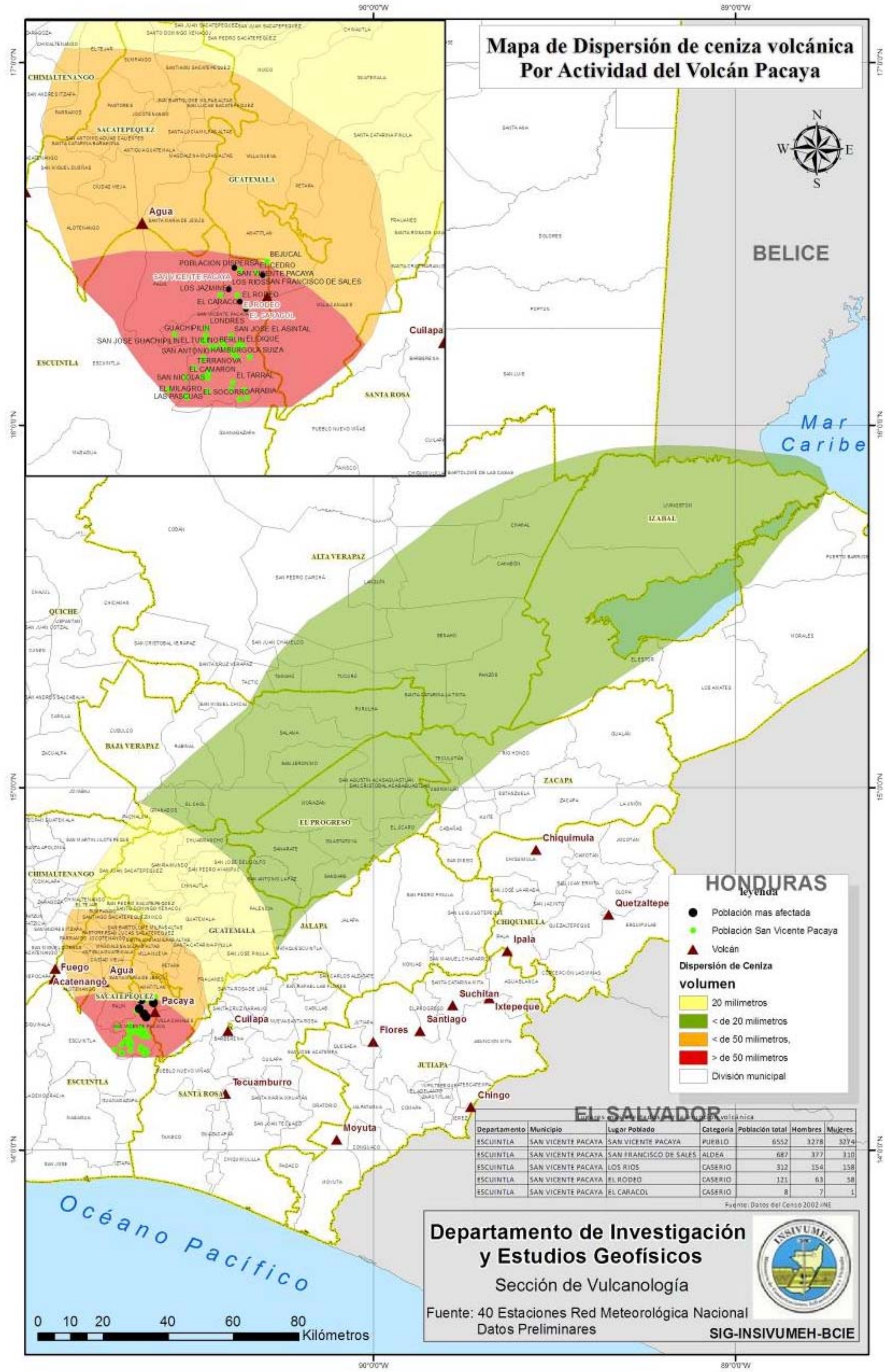
There was increased seismicity 36 hours prior to the onset of the eruption, giving some warning. Access to the summit had been closed to the public for two days before the eruption; tour guides had been taking tourist parties to see lava flows and this was judged to be too dangerous.

2.3.1 27 May 2010 eruption

At 14h15 on 27 May, Strombolian eruptions began at MacKenney crater. These reached heights of 500 to 600 m above the crater. Tephra plumes rose 1.5 km above the crater and drifted west and southwest. The community of El Patrocinio (Figure 1.3) evacuated, and residents in nearby El Rodeo were ordered to evacuate (see section 5.3.1 for further detail). Authorities instructed residents to clear tephra from their roofs and to avoid driving. Between 14h00 and 17h00 there were two pyroclastic flows to the south. The most violent paroxysmal phase of the eruption began at 19h09 and lasted for 45 minutes. The eruption generated a 3 km high column. The west side of MacKenney crater collapsed, resulting in a directed blast to the north. The wind was also blowing to the north and debris were thus distributed mostly on the northern side (Figure 2.5). This came as a surprise as previous recent experience has been that tephra has fallen to the south and southwest of the volcano. Heavy tephra falls combined with the threat of ballistic bombs and blocks lead to approximately 1600 people being evacuated from communities from the western, northwestern and northern sectors (see section 5.3.1 for further detail).

2.3.1.1 Tephra dispersion

We received estimates of tephra dispersion and deposition from two sources: a report by Escobar Wolf (2011), and from staff of INSIVUMEH. According to Escobar Wolf (2011), tephra was dispersed to the north and northeast of the volcano over an area greater than 1000 km^2, and the measured thicknesses of tephra deposits were 47 cm at a distance of 1 km from the vent, to a few mm at distances of over 70 km. A map provided by INSIVUMEH (Figure 2.6) shows ash dispersion to the northeast coast of the country, a distance of approximately 350 km. Staff of INSIVUMEH provided the following estimates of tephra fall thicknesses: San Francisco de Sales, located less than 3 km north of the crater, received 20 cm tephra fall; Lago Amatitlán (Figure 1.2) received '15 cm hot tephra fall'. This reportedly caused significant damage to crops; In San Vicente Pacaya, a resident we interviewed reported that approximately 2.5 cm of tephra fell over 45 minutes. The tephra was mostly sand-sized with occasional larger clasts (Figure 2.7), and was 'red and black' in colour.



Departamento	Municipio	Lugar Poblado	Categoría	Población total	Hombres	Mujeres
ESCUINTLA	SAN VICENTE PACAYA	SAN VICENTE PACAYA	PUEBLO	6552	3278	3274
ESCUINTLA	SAN VICENTE PACAYA	SAN FRANCISCO DE SALES	ALDEA	687	377	310
ESCUINTLA	SAN VICENTE PACAYA	LOS RIOS	CASERIO	312	154	158
ESCUINTLA	SAN VICENTE PACAYA	EL RODEO	CASERIO	121	63	58
ESCUINTLA	SAN VICENTE PACAYA	EL CARACOL	CASERIO	8	7	1

Fuente: Datos del Censo 2002 INE

Figure 2.6 Map of tephra dispersion and deposition (source: INSIVUMEH).

In Guatemala City, tephra fell mixed with rain. Escobar Wolf (2011) reports that 'the grain size of the tephra that fell in Guatemala City ranged from sub-mm to cm size and the clasts consisted of black to dark brown vitric (crystal-poor) scoria' (Figure 2.7). Many interviewees in the current study described the tephra as *arena* or sand (Figure 2.8). Thicknesses reported by Escobar Wolf (2011) ranged from 10 cm on the shores of Lago Amatitlan, to 0.5 cm in the central city. This author states that thicknesses exceeding 'a few cm' at these distances (~30 km from the volcano) should be regarded with caution, and he considers it most probable that the south part of the city may have received up to 3 cm tephra fall whereas the rest of the city probably received in the region of 1-2 cm. These estimates are in accordance with depths reported by interviewees for our study. The Airport Manager estimated that a total of 2-3 cm of tephra fall was received at the airport. Similarly, the Maintenance Manager of the hospital B San Juan de Dios, located in the northern sector of the city, estimated a similar total thickness of 2-3 cm tephra fall. A map prepared by the city's municipality showing relative impacts is shown in Figure 2.9.

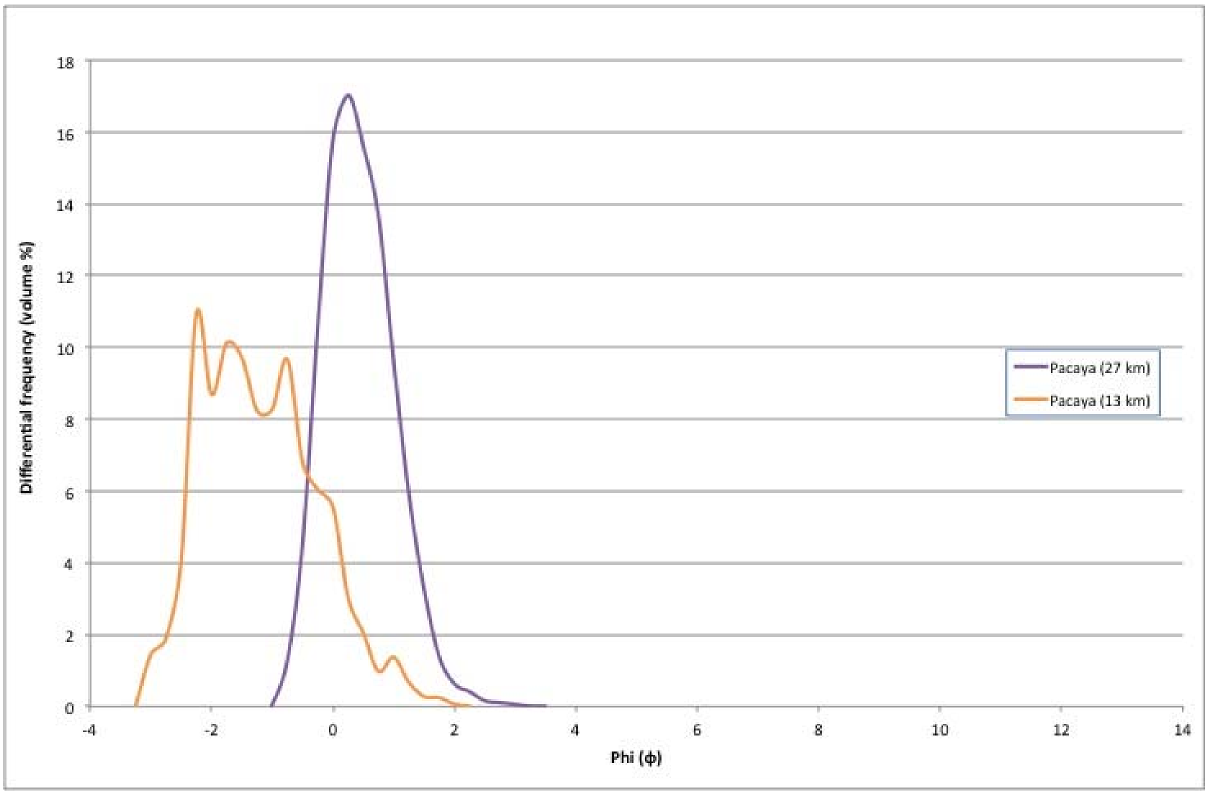


Figure 2.7 Grain size distributions for volcanic tephra samples collected from Villa Canales (13 km from vent) and La Aurora International Airport in Guatemala City (27 km from vent). N.B. samples were collected ~4 months after the eruption and may have been altered by external processes (e.g. crushing from human traffic, environmental factors, etc.).

Figure 2.8 Coarse, 'sand-sized' tephra deposited in Guatemala City.

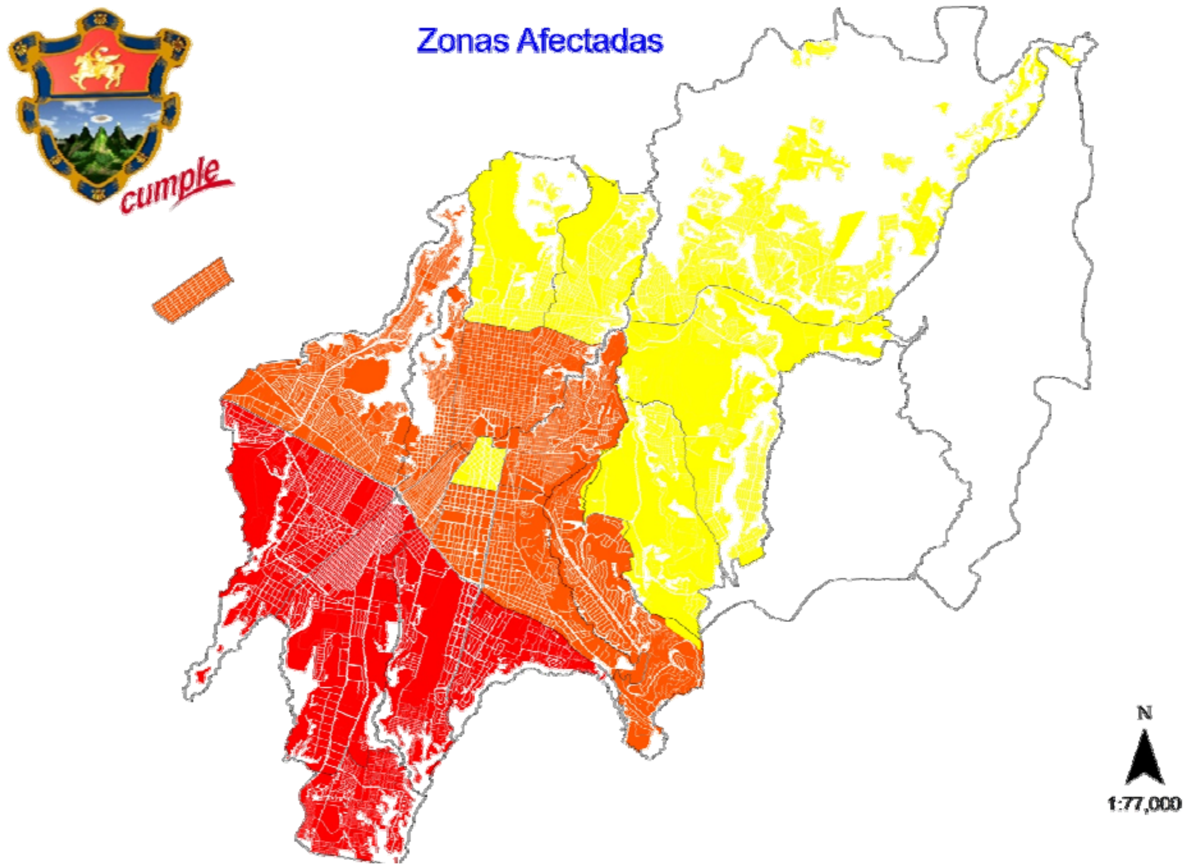


Figure 2.9 Impacts of tephra fall on Guatemala City, with worst-affected areas shown in red and least-affected areas in yellow (source: Municipality of Guatemala City).

2.3.1.2 Ballistic clasts

The report by Escobar Wolf (2011) includes a thorough assessment of the impacts of ballistic clasts ejected during the paroxysmal phase of the eruption. At Cerro Chino crater, approximately 1 km from the vent, clasts exceeding 0.5 m in size (long axis) fell, smashing concrete roofs, destroying vehicles both by impact and by starting fires, and knocking down radio towers (Figure 2.10). A news reporter in the vicinity at the time was killed, and others injured.

Figure 2.10 Ballistic clast damage to radio masts, building and vehicle in vicinity of Cerro Chino (photos: Gustavo Chigna, INSIVUMEH).

Further afield, the villages of El Cedro, San Francisco de Sales and Calderas (Figure 1.3) were all significantly affected by ballistic block fall. These villages are all located between 2.5 and 3.5 km from the vent, to the north. The maximum distance at which ballistic impact damage was reported was 4 km (Escobar Wolf, 2011). Damage caused by the fall of ballistic clasts is described further in Section 4.0.

The range that ballistic blocks were thrown is somewhat greater than the typical reported range for Strombolian eruptions (Parfitt and Wilson, 2008); for instance, these authors report that for the 1973 Heimaey eruption blocks of 0.2 m diameter were thrown 500 m. This may be because the eruption may not have been vertically directed, but directed towards the north due to partial collapse of the crater (INSIVUMEH staff; Escobar Wolf, 2011).

2.3.2 Activity from 28 May onwards

The eruption continued on 28 May, with a further large eruption generating a column of 1 km height. On 29 May, a 90 m wide lava flow travelled SSE at an estimated rate of 100 m per hour and burned three houses. The flow also disrupted an access road between El Caracol and Los Pocitos (See Figure 1.3). The energy liberated during the eruption (RSAM, or Real-Time Seismic Amplitude Measurement) is shown in Figure 2.11, and various phases of the eruption are illustrated in Figure 2.12.

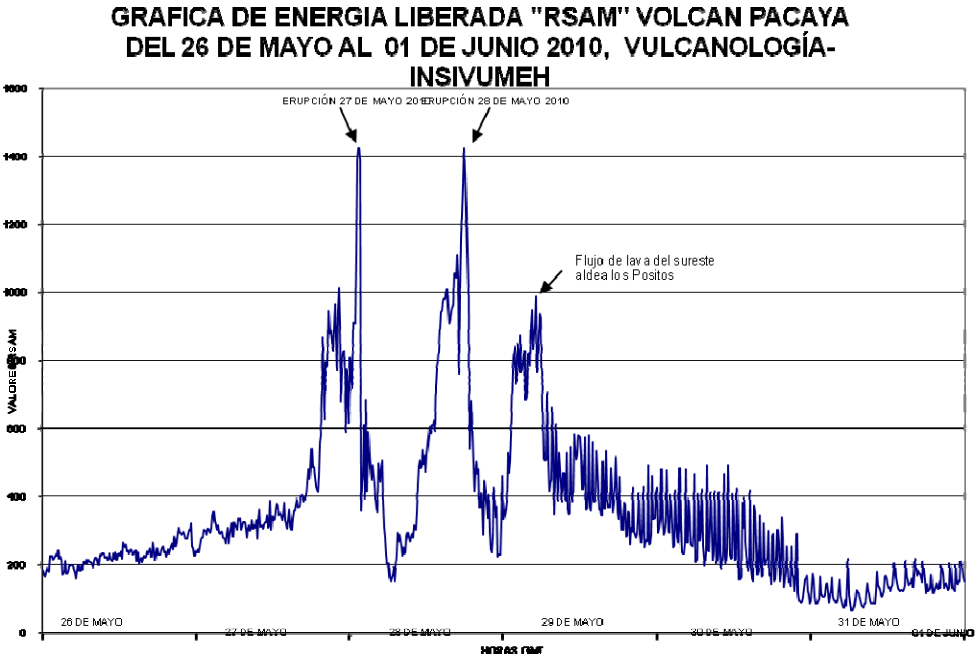
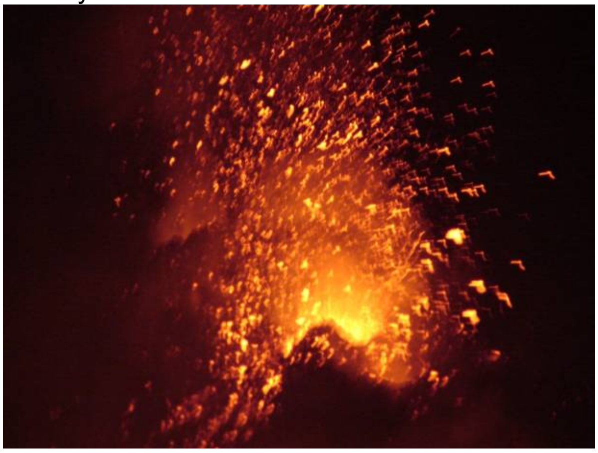


Figure 2.11 Energy liberated during 27-28 May 2010 eruptions of Pacaya volcano (source: INSIVUMEH).

27 May 15h31

27 May 16h31

27 May 20h09



28 May

Figure 2.12 Phases of eruption of Pacaya volcano commencing 27 May 2010 (photos: INSIVUMEH).

Strombolian activity at MacKenney Cone continued into June and July, decreasing in magnitude. On 13 July an explosion generated a tephra plume that rose 300 m above the crater and drifted southwest. On 22-25 July there was further Strombolian activity. A plume rose to an altitude of 4.6 km causing tephra fall up to 10 km distant, and ejected blocks fell on the flanks of the cone. Over time the activity became predominantly effusive (Figure 2.13) with a major new lava flow to the south.

The May 2010 eruptions created a new NNW-trending trough on the flank of MacKenney Cone (Figure 2.14). Considering both the maximum height of the plume of 3 km above the vent and a minimum estimated tephra volume of 1.3×10^7 m^3 (Escobar Wolf, 2011), the 27 May 2010 eruption of Pacaya can be classed as VEI 2-3.

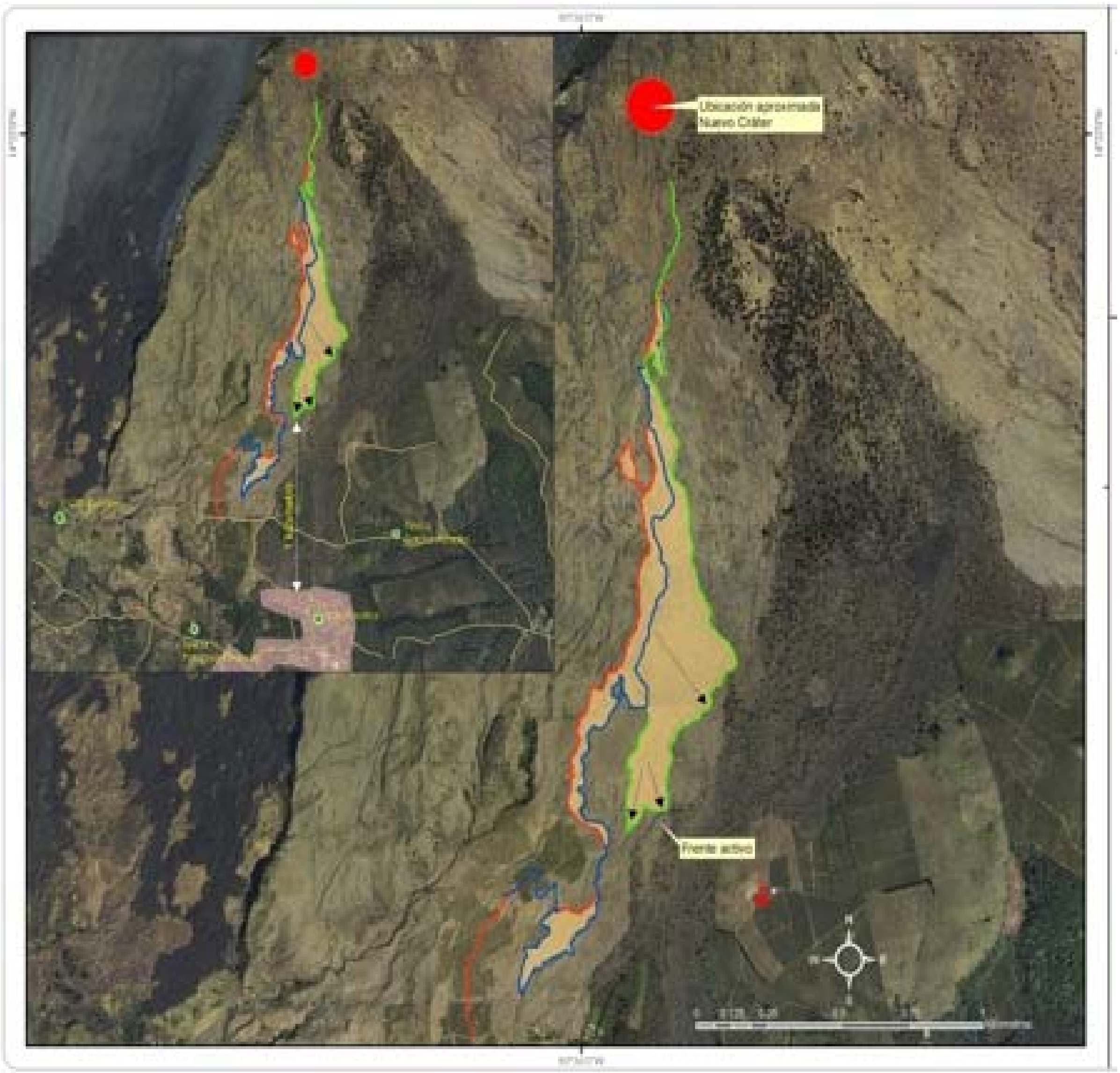


Figure 2.13 Lava flows from Pacaya volcano in June 2010. The red line marks the boundary of the 4^{th} June flow, the blue line marks the edge of the flow on the 8^{th} June and the green line marks the extent of the 15^{th} June lava flow. The yellow shaded areas show the total area affected by the flows (adapted from INSIVUMEH report 1402-11).

Figure 2.14 Post-May 2010 NNW trending trough on MacKenney Cone (compare to Figure 2.4)(photo: INSIVUMEH).

2.4 Tropical storm Agatha

On 29 May 2010, Guatemala was hit by a major tropical storm (Figure 2.15).

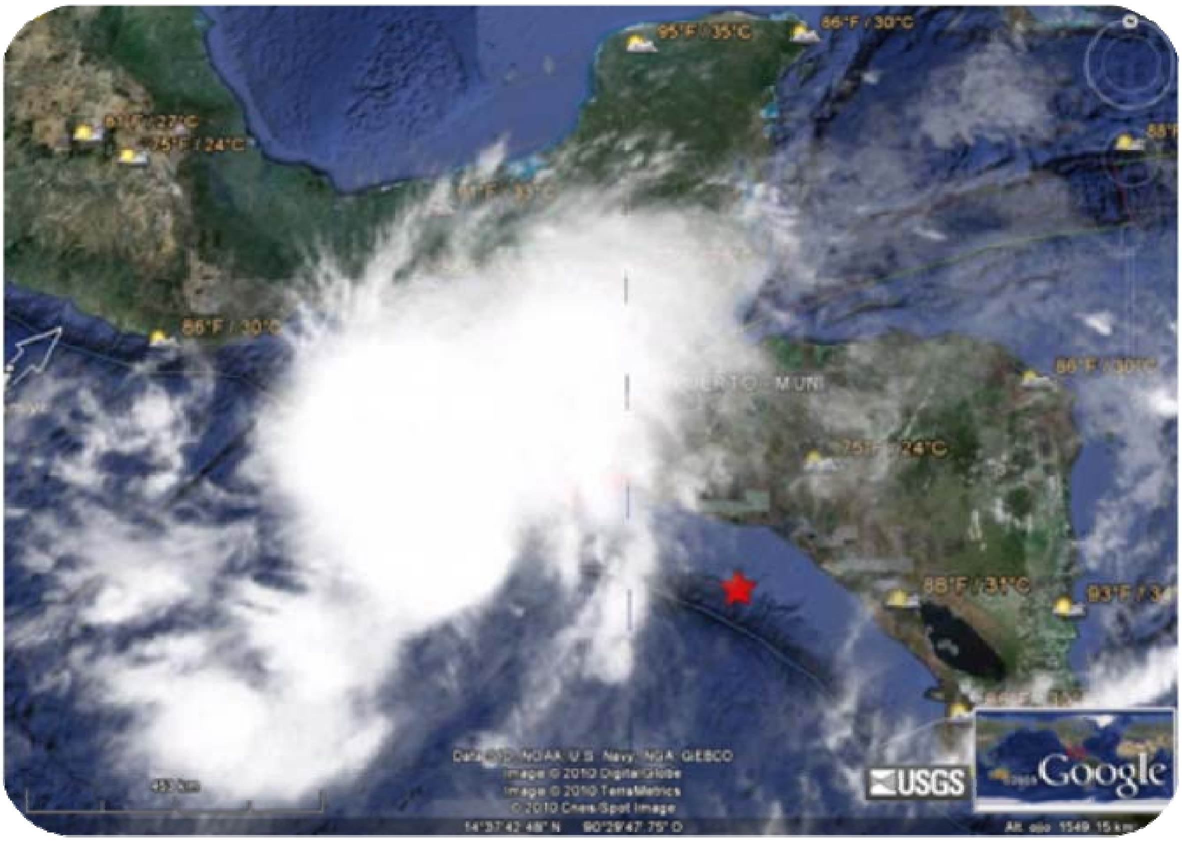


Figure 2.15 Tropical storm Agatha approaches Guatemala, 29 May 2010.

This storm caused major damage across central and southern Guatemala (Figure 2.16). According to CONRED Information Bulletin No. 1673 (2010), issued to mark the one-year anniversary of the combined eruption/tropical storm disaster, the storm affected 395,291 people, caused 168,059 people to be evacuated and left 111,020 people in temporary shelters. One hundred and sixty people were killed, 79 wounded, 37 were reported missing and more than 38,000 homes were damaged. There was also heavy damage to infrastructure, particularly the highway system, with numerous landslides and road and bridge washouts. The impacts of the storm in conjunction with the eruption are discussed for each sector in the remainder of this report.

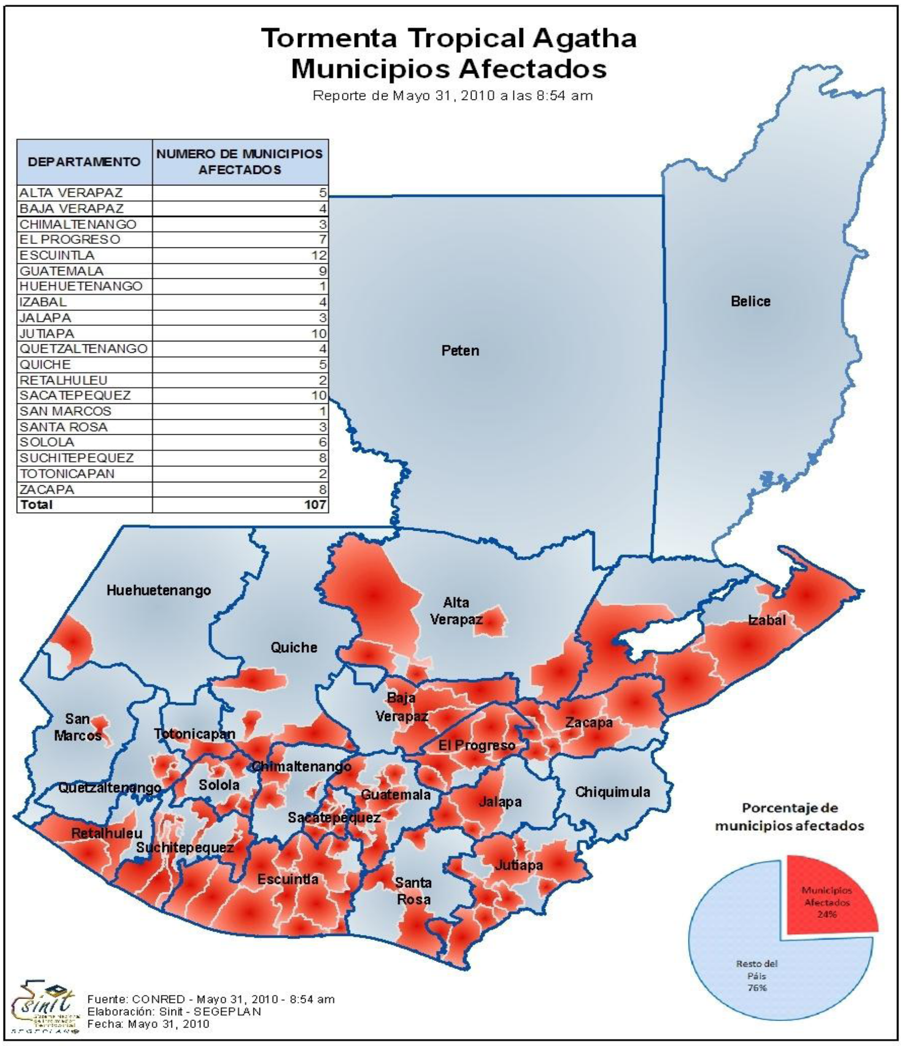


Figure 2.16 Municipalities affected by tropical storm Agatha (source: Municipality of Guatemala City).

3.0 INFRASTRUCTURE IMPACTS AND RESPONSES TO RECENT TEPHRA FALL

3.1 Electricity supply

Electricity supply systems are vulnerable to interruption from volcanic tephra fall hazards. Previous studies suggest that volcanic tephra contamination of electricity transmission (e.g. > 69 kV) and distribution equipment (e.g. < 69 kV) can disrupt the provision of electricity to society in the following ways (after Wilson et al., 2009b):

- Tephra accumulation on HV (e.g. > 33 kV) insulators can lead to flashover (the unintended electric discharge over or around an insulator), which often leads to the disruption of service. When flashover occurs on transformer insulation (bushings), this can cause damage to the apparatus and will most certainly result in the disruption of power supply.
- Line breakages and damage to towers and poles due to tephra loading, both directly onto the structures and by causing vegetation to fall on to lines, particularly in heavy, fine tephra fall events.
- Snow and ice accumulation on lines and overhanging vegetation will further exacerbate the risk.
- Breakdown of substation and generation facility control equipment; such as air conditioning/cooling systems due to tephra penetration which can block air intakes and cause corrosion.

3.1.1 Organisational structure of the electrical network in Guatemala

The Comision Nacional de Energia Electrica (CNEE) supervises the energy wholesale market in Guatemala. Under CNEE is the self-financing government entity titled Instituto Nacional De Electrificacion (INDE) whose job is to ensure the constant and safe supply of electricity at a transmission level. Empresa de Transporte y Control de Energia Electrica (ETCEE) is a subsidiary company of INDE that is in charge of managing, operating and maintaining the electricity transmission (>69 kV) and distribution (<69 kV) in terms of quality prescribed by the General Electricity Law. Several privatized companies have been established to physically transmit energy at a distribution level (e.g. Empresa Electrica de Guatemala (EEGSA)), but these companies ultimately look to the CNEE for direction.

Guatemala’s electricity network traverses a diverse terrain to provide energy to its 14.4 million inhabitants. Guatemala operates its transmission system at voltages of 69, 138, 220 and 400 kV to meet a national demand of 1450 MVA. As it stands, the total generation capacity for Guatemala’s electricity network is approximately 1700 MVA. Thirty percent of the 1450 MVA network demand is generated by hydro facilities, while the other 70% is produced by thermal (combustion and geothermal) enterprises. Guatemala sometimes buys electricity from Mexico and on-sells to El Salvador.

This section provides a summary of the information gathered from interviews with personnel from ORMAT’s Amatitlán geothermal plant, EEGSA, INDE and ETCEE.

3.1.2 Generation sites: impacts on Amatitlán geothermal plant

In Guatemala, the geothermal development company ORMAT Technologies Inc. owns and operates several geothermal plants. The Amatitlán plant is located on a geothermal field situated immediately north of San Francisco de Sales, and approximately 3 km north of the active vent of Volcán Pacaya (Figure 3.1). The plant currently generates 18 MVA at a voltage of 13.8 kV. This voltage is then stepped up to 138 kV for integration into the national grid via the Palin substation.

During the 27 May 2010 eruption, the San Francisco de Sales area received an estimated 20 cm of tephra, ranging from coarse (e.g. >1.5 mm) to lapilli-sized. Ballistic bombs and blocks (up to 25 cm diameter long axis) also fell in this area, and extensive damage was caused locally. At the Amatitlán plant, the worst damage was to steam condenser fans and roofs. As the fans were uncovered, fan blades suffered abrasion damage from tephra fall as well as denting and bending from falling blocks which rendered the damaged units nonoperational (Amatitlán plant operator). Three fan blades needed to be replaced. Cleaning of fans was slow (days to weeks), as it required the use of vacuum cleaners to remove particles from the intricate arrangement of fan blades, cooling fins and condenser coils. Operations were discontinued immediately after the eruption and the plant remained offline for three weeks while cleaning and repairs were carried out.

Other issues encountered by plant personnel were minor denting of the intake and outlet pipe cladding (Figure 3.2) and the removal of tephra from the switchyard gravel. No pipes required replacement or repair and no reduction in thermal efficiency was observed. Removal of tephra from switchyard gravel required complete sieving over a several day period to separate it from the volcanic material. Tephra was removed from the switchyard gravel due to health concerns over the material being broken up further and creating a fine dust that could have caused respiratory problems. No issues of corrosion were reported. Also, no ceramic insulation (insulators and bushings) was damaged by the ballistics.

Figure 3.1 Amatitlán geothermal plant.

Figure 3.2 Superficially damaged pipe cladding at the Amatitlán geothermal power plant (dent is approximately 20 cm wide).

The arrival of tropical storm Agatha on 29 May 2010 (two days after the initial eruption) did not cause any further issues for the Amatitlán plant as staff had already been evacuated and the plant’s operations suspended because of the bombardment of volcanic debris.

The El Reigno hydroelectric dam, located some 10km from Pacaya volcano on Lake Amatitlán, was also reported to have suffered damage following the 27 May eruption (EEGSA network operator). Details of the damage were not obtained on this reconnaissance trip.

3.1.3 Transmission and distribution equipment

EEGSA is a distribution supply (<69 kV) company that provides electricity to three of Guatemala’s 22 departments (Figure 3.3).

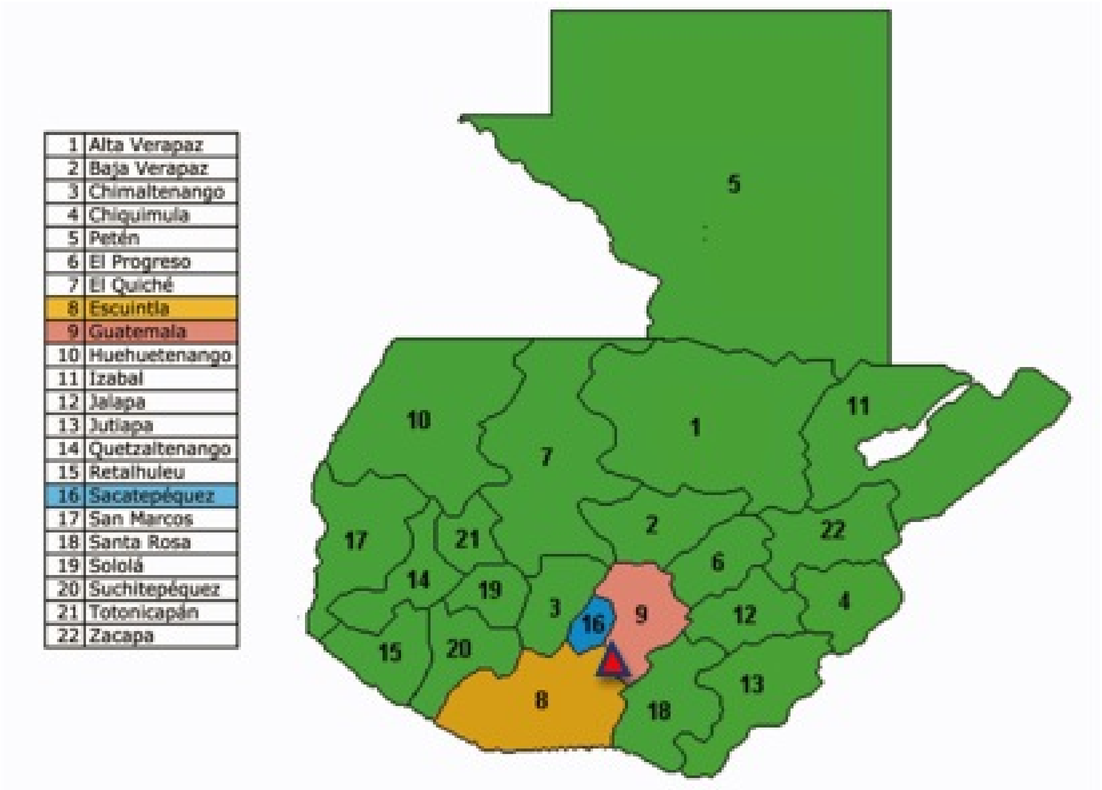


Figure 3.3 Guatemalan administrative departments. Highlighted departments represent those supplied with power by EEGSA. The approximate location of Pacaya volcano is denoted by the red triangle.

Although they comprise only four percent of the nation’s total land area, the departments of Guatemala, Sacatepeguez and Escuintla and their 940,000 inhabitants consume nearly 50% (roughly 625 MVA) of the nation’s total energy demand. Within these departments, EEGSA owns and operates 53 distribution substations and 6 transmission stations.

EEGSA reported numerous issues due to volcanic tephra contamination. Rain during the eruption added to the risk of tephra contamination of high voltage equipment flashing over, and several earth faults occurred. Specifically, there were six 69 kV circuits that endured continual flashover despite several attempts to re-close the circuits. Of these, Guadelupe lines 1, 2 and 3 were particularly problematic (we suspect that this was most likely due to increased tephra thicknesses at their location(s)) (EEGSA network operator). On 28 May 2010 (the day after the eruption) a 25.88 MW load was shed from a 69 kV circuit causing a two-hour long outage (EEGSA Operations Manager). Despite several reports of faulting on the system no burning or physical damage of transmission equipment was noted, thus no replacement or repair of equipment was required.

Porcelain or composite polymer are the most common insulator materials used on Guatemalan transmission circuits with composite polymers rapidly becoming preferred due to their low cost and weight and superior hydrophobic properties (Okada et al., 2002).

3.1.4 Substations

While INDE reported no faults with Guatemala's transmission system following the 27 May eruption, distribution substations responsible for stepping down transmission voltages experienced several adverse events. Several EEGSA substations received coarse tephra fall out during the 27 May eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano.

Figure 3.4 Coarse tephra deposited at Laguna substation (see Figure 3.5 for location)(photos: EEGSA)

The EEGSA substations that received the most tephra fall were scheduled for extensive offline cleaning on May 29 and 30. However, the onset of tropical storm Agatha hindered the cleaning procedure and large amounts of tephra remained on substation equipment during the early hours of the storm. The combination of tephra contamination, together with heavy rain from the storm, caused further faulting (flashovers) on the system, with several interruptions occurring throughout the event (29-30 May)(EEGSA network operator). With the passing of Agatha it was found that the rains had sufficiently cleaned all substation equipment and none but the Laguna substation (located ~5 km from the vent) required further cleaning (Figure 3.4). Power transformer bushings were said to be the most important components to clean, as flashover across the bushing would likely cause irreparable damage to the transformer. The transformers themselves were described as being the most problematic and difficult apparatus to wash free of tephra because of the intricate array of cooling fins and sensitive components vulnerable to further damage from abrasion or water/tephra ingress. As a preventive measure, tephra was cleaned from transformer radiator fins to allow sufficient heat transfer and cooling of the apparatus.

ETCEE manages two large (230 kV) substations which were affected by the eruption. These stations (Guate Sur and Guate Este) required offline cleaning shortly before the arrival of the tropical storm (Figure 3.5). One of four transformer banks was de-energised at a time and each bank remained offline for a period of two hours. Cleaning involved the sweeping and brushing of tephra from substation hardware and surrounding yards. This tephra was shovelled and trucked away to a nearby area to serve as landfill. Substation gear was subsequently washed using high-pressure water pumps.

Historically, no electricity supply company in Guatemala has observed reduced resistivity (increased conductivity) in substation gravels (and therefore no increase in step-touch potentials) due to tephra contamination (EEGSA network operator). Thus no effort was made to perform resistivity measurements, sieve out the tephra or to replace the gravel. At the time of our visit tephra was still mixed in with the substation gravel at Amatitlan plant.

There were no reports of abrasion or corrosion damage at any of the affected substation sites.

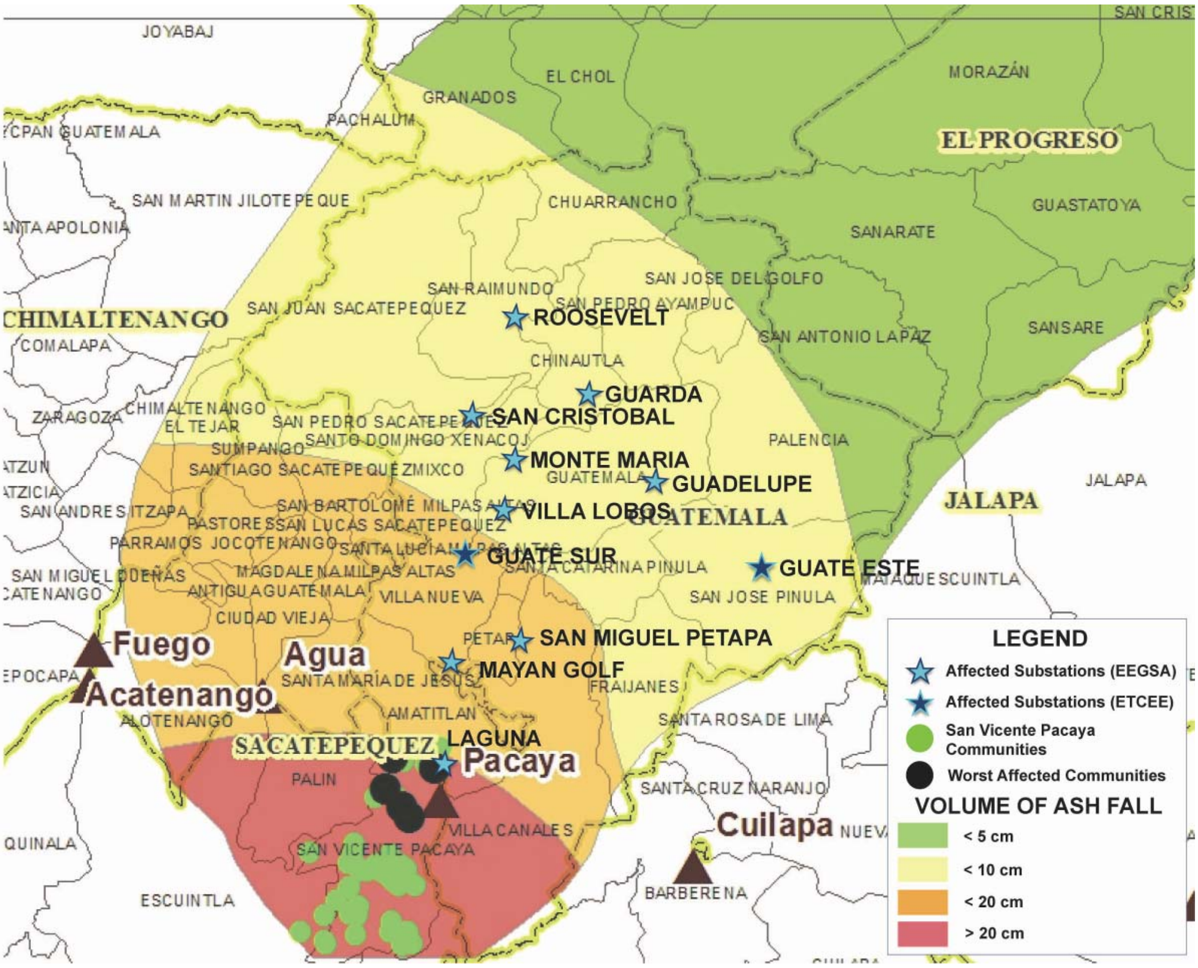


Figure 3.5 Isopach map of 27 May 2010 eruption showing approximate location of affected substations. Blue stars represent substations and their names are juxtaposed (adapted from INSIVUMEH map).

3.1.5 Summary

ORMAT's Amatitlán geothermal plant received ~20 cm of mostly lapilli-sized tephra. Ballistic bombs and blocks also bombarded the plant, causing extensive damage to the plant's roof and condenser fans. Fan blades were dented, bent and also suffered damage from abrasion. Minor denting of the intake and outlet pipe cladding was also reported however these impacts were superficial and did not require repair. Removal of tephra from the plant's surface gravel was carried out to avoid health concerns over the material being broken up further and creating a fine dust that could have caused respiratory problems. Operations were discontinued immediately after the eruption and the plant remained offline for three weeks while cleaning and repairs were carried out. The onset of Tropical Storm Agatha had little impact on the plant, as it was not operating at the time.

Guatemala's transmission network (>69 kV) did not experience any issues from the May 2010 eruption of Pacaya volcano. However, EEGSA experienced numerous issues of flashover on its distribution circuits due to volcanic tephra contamination combined with rain at the time of fall out. Six 69 kV circuits were unable to be brought online due to continual flashover on 27 May and, on the following day, a 25.88 MW load was shed from a 69 KV circuit causing a two-hour long interruption of supply.

Several EEGSA substations received coarse tephra fall out during the 27 May eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano. Laguna, the closest substation to the volcano, was immediately shut down as a precautionary measure. An extensive cleaning program originally scheduled for May 29 and 30 was halted due to the onset of Tropical Storm Agatha which caused further instances of flashover on EEGSA's distribution network. ETCEE's Guate Sur and Guate Este substations were cleaned (offline) immediately following the 27 May eruption by sweeping and brushing tephra from substation hardware and surrounding yards.

There were no reports of corrosion, abrasion or increase in step-touch potentials at any of the affected transmission or distribution facilities.

3.2 Water supplies

3.2.1 Overview

Guatemala has an abundance of freshwater, with 18 major rivers originating in the volcanic highlands. While there is adequate water to meet water demands for the population overall, the major population centre (Guatemala City and the Metropolitan Region) is under water stress as it is located on the Continental Divide and surface water resources in this area are scarce and vulnerable to contamination.

An assessment by the US Army Corps of Engineers (2000) concluded that the water supply sector in Guatemala at that time was characterized by low and inconsistent service coverage, especially in rural areas; unclear allocation of management responsibilities; and little or no regulation and monitoring of service provision. A more recent report (Pagiola et el., 2007) for the World Bank also noted that Guatemala was at that time the only Central American country not to have a national public corporation to manage domestic water supply. Since then, a National Water Commission (CONAGUA) has been established to implement the mandates of the National Water Law.

Access to water and sanitation services has slowly risen over the years in Guatemala. However, particularly in rural areas, the rate of households with a piped water supply remains below development goals (Table 3.1).

Table 3.1 Household water and sanitation coverage in Guatemala (%) (data: 2002 census).

	Total	Urban	Rural	MDG[1]
Water supply	74.6	89.5	59.5	82
Sanitation	46.9	76.7	16.8	66

[1] Millennium Development Goals

Guatemala's drinking water standards are based on the World Health Organisation standards. Their implementation is overseen by the COGUANOR committee which is attached to the Ministry of Economy. COGUANOR is a member of the International Organisation for Standardisation (ISO).

3.2.2 Guatemala City

In 1972 the Municipality of Guatemala created a municipal water company (EMPAGUA) to manage the city's water services. EMPAGUA serves 85 percent of the city's water users, with the balance being provided by a private firm, Aguas de Mariscal ((Pagiola et al., 2007) which supplies about ten percent of Guatemala City and some smaller firms and private groundwater wells which supply the remaining five percent.

The following discussion refers only to information obtained from interviewing the technical director of EMPAGUA.

For Guatemala City, there are two sources of water: surface water and groundwater, each supplying about 50 percent of production capacity. EMPAGUA's average production rate is 4000 litres per second. The system serves 1.8 million people. There are major problems with the quality of surface water due mostly to agricultural runoff and poor sewage disposal practices. Contaminants include turbidity, BOD, COD, nutrients, pathogenic microorganisms, iron, fluoride and sulphate. Turbidity is a major challenge for water treatment plants; in winter it can be as high as 15,000 NTU (Nephelometric Turbidity Units) in surface waters whereas in summer it is typically 10-30 NTU. There are fewer problems with groundwater quality although contamination with iron and manganese can be a problem and the temperature of the groundwater resource is high (37ºC) and it has to be cooled. The two sources are fed into the same distribution network.

There are five treatment plants of varying ages. One of the older plants can only treat raw water with turbidity <400 NTU, but other plants can cope with higher levels in intake waters. Water treatment consists of the addition of chemical flocculants (alum, lime, polyelectrolytes), pH adjustment with lime, sedimentation for 3-4 hours, then chlorination. Parameters measured in raw water are temperature, colour, turbidity and pH.

3.2.2.1 Problems caused by the eruption

Previous eruptions of Pacaya volcano have not caused any issues for EMPAGUA, but the eruption of 27 May did cause them a number of problems. The eruption deposited coarse (sand-sized) basaltic tephra on Guatemala City (Figure 2.6). The tephra caused abrasion damage to air-cooled motors and they stopped straight away. Tephra was also deposited in the open-air tanks. One tank in particular had a volume of 7000 m^3 and was open, so was contaminated by the airfall deposits. Turbidity increased, with larger particles sinking to the bottom, but some smaller particles remaining in suspension. The tephra fall also affected the groundwater wellhead pumps.

EMPAGUA did not attempt to treat the water, but opted to clean out the tanks. Thus there was no need to increase chlorination levels to compensate for increased turbidity. The cleaning operation took three days. Production rates were affected, with tanks that were being cleaned being bypassed. However the director said that an erratic water supply is not unusual in Guatemala and that the public have adaptations to this situation such as on-site home storage tanks. Thus his view was that disruption would probably have been minimal to end-users.

The director's overall assessment was that the main impacts of the eruption were that it necessitated increased maintenance of storage tanks, and cleaning filters. There were no real water quality problems because contaminated tanks were cleaned out rather than treated.

EMPAGUA's approach to site cleanup was to sweep up tephra from roads and parking areas to stop the tephra being crushed and remobilised by vehicle traffic. Roofs and gutters had to be cleaned out as gutters broke under the weight of the tephra.

When asked what lessons they had learned and what they might do differently in the future, the director said that they would cover up equipment. It could be a challenge for them to cover large tanks (their largest tank is 70 m diameter) but he thought it would be worthwhile to prevent future episodes of contamination by volcanic debris. He also said that they would cover the groundwater wellhead pumps.

EMPAGUA are critically dependent on the electricity supply for pumping groundwater. They often experience problems with their power supply in winter anyway due to tree fall on lines during stormy weather. EMPAGUA's personal substations had to be cleaned to prevent flashover following the tephra fall. The eruption also caused widespread line damages and breakages which affected the electricity supply. There are three large plants in Guatemala City that have their own on-site substations, as it requires large amounts of power to pump water 500 metres uphill. These substations provide a voltage of 69 kV however there are also smaller plants that only require 13.8 kV and 4.64 kV.

The municipal cleanup, following the tephra fall, was prompt and efficient (Section 3.5.1). EMPAGUA was asked to be a member of an emergency committee coordinated by the municipality to oversee the cleanup and disposal of the tephra. The director was unsure whether the cleanup created extra water demand; it is difficult to measure water use because the citizens are already accustomed to an erratic water supply (access varies from six hours to 24 hours service per day) and many people have adapted to this uncertainty by installing extra storage tanks on their properties.

3.2.3 Impacts in San Francisco de Sales

The town of San Francisco de Sales is located approximately 3 km from the active vent of Pacaya volcano, on the northern slopes of the volcano (Figure 1.3). Its water supply comes from springs and streams higher on the mountain, and is piped to the town using an above ground distribution network of PVC piping (3/4" diameter, 250 psi). The pipework suffered extensive damage from ballistic blocks and bombs during the eruption and the town lost its water supply for eight days while the damaged pipes were replaced.

3.3 Wastewater systems

Volcanic tephra fall can cause damage and disruption to wastewater systems (both sewage and stormwater). Tephra can enter and block pipes and sumps, can cause accelerated wear on motors and pumps, and can cause serious damage to wastewater treatment plants (Wilson et al., 2011a). Tephra can enter treatment plants both via sewer lines (particularly if these are combined with stormwater lines), and by falling directly on treatment facilities.

The following information was obtained primarily from interviewing the General Manager of the company Mapreco. This company was founded 25 years ago, and has the maintenance contracts for 90 percent of wastewater systems in Guatemala City. They also advise on wastewater treatment plant design and maintenance.

This section covers only sewage treatment systems. Impacts of the tephra fall on the city's stormwater drain system are described in Section 3.5.1.

3.3.1 Overview of wastewater disposal in Guatemala City

Guatemala City is located on a drainage divide which runs approximately through the middle of the city along a NW/SE axis. In the north of the city, there is a combined stormwater-sewage system for household water plus stormwater which drains to the Las Vacas and Motagua rivers then to the Gulf of Honduras. To the south, surface waters drain to Lago Amatitlan (Figure 1.4) and then to the Pacific Ocean. Contamination of surface waters by untreated sewage is a major problem in Guatemala, and the Las Vacas and Villalobos rivers and Lago Amatitlan are considered to be severely contaminated.

There has been international pressure to improve environmental management in Guatemala, particularly with respect to the disposal of untreated sewage. A law mandating the quality of waste disposed to the environment has been in force since approximately 2002, but specific regulations to enforce this law were only introduced in 2006 (MARN, 2006). Domestic and industrial wastewater discharges must now meet environmental quality standards. Systems in the north of the city were allowed an extra decade to comply with the new standards as this is the oldest part of the city and the infrastructure is correspondingly older. These standards are not prescriptive about what treatment methods should be used; they monitor the end results.

3.3.2 Wastewater treatment systems in Guatemala City

Guatemala City has hundreds of wastewater treatment plants ranging in size from those serving just a few households to larger facilities such as the plant serving the University of San Carlos. This system utilises an Imhoff tank (a combined sedimentation and sludge digestion tank, see Figure 3.5).

Some of the larger plants were constructed by EMPAGUA in the early 1990s; these are now considered old in design, and their treatment capacity is routinely exceeded. The largest plant (Belo Horizonte) receives ten times more wastewater than its capacity, and has to bypass the plant and discharge to the environment. The Nimajuyu plant located west of Zone 11 processes approximately 800 m^3 of wastewater per day.

Most of the larger wastewater treatment plants have coarse static screens that are bars spaced approximately 2.5 cm apart, rather than using fine mesh screens which would require too much maintenance. Mapreco staff were unaware of any plants which have pre-screening treatment with moving parts such as bar, step or rotating drum screens. Most systems are thus relatively simple and robust. Plants generally have a primary sedimentation tank followed by secondary treatment using either aerobic or anaerobic waste stabilisation ponds. They may then have a polishing step using rocks or gravel filter beds. In some cases the waste is treated with calcium hypochlorite to disinfect it.

Figure 3.6 Cleaning out Imhoff tank at University of San Carlos, Guatemala City (photo: Mapreco).

3.3.3 Impacts of the eruption

The 27 May tephra fall had widespread impacts on Guatemala City's wastewater treatment facilities. The tephra received in the southern part of the city was coarser and sandier in texture, whereas the northern part received finer ash. Mapreco reported that for wastewater treatment plants it was a 'double problem' having the heavy rains brought by the tropical storm after the tephra fall as more tephra washed into wastewater systems before they had a chance to clean it up.

Tephra entered wastewater treatment systems both via sewer lines and by direct deposition into ponds. Mapreco staff described the impact on one particular system (the system at the University of San Carlos, shown in Figure 3.6) in some detail. Approximately 4-5 metres of tephra accumulated in the Imhoff tank. The removal process consisted of mixing the tephra with the sludge so that the heavy tephra sank to the bottom. Then sludge pumps (15 cm internal diameter piping) were used to remove the lighter material on top, and the rest was dug out manually. There was heavy wear and tear on this equipment due to abrasion damage to propellers (Figure 3.7). Their normal lifetime of two years was reduced to 15 days. It was generally difficult cleaning out tephra-contaminated sludge as the tephra was reportedly very dense and 'hard to shift' with a hose. The same approach (using a suction pump to remove the lighter material then shovelling out the denser material) was used for many different types of treatment plants, such as small aerobic plants used to service condominiums (Figure 3.8).

In general, the tephra was difficult to handle. It was heavy and abrasive and could not be moved with a hose very easily. It was also heterogeneous in grain size (Appendix 3).

Figure 3.7 Sludge pump propeller of the same type that suffered severe abrasional damage from volcanic tephra.

Wastewater systems generally took between 2-3 days and a week to clean out, depending on their size and difficulty of access. At the time of our visit, Mapreco were still receiving calls. The company estimated that additional business generated by the eruption increased their profits by 20%.

The company noted that blockages of storm drains and sewers continued to be a problem for months after the eruption, and was still causing flooding at the time of our visit.

Figure 3.8 Aerobic digestion tank, small-scale wastewater treatment plant serving condominium development (photo: Mapreco).

3.3.4 Lessons learned

Even though Guatemala City is within range of several recently active volcanoes, Mapreco's view was that it was not ready for an eruption and that people did not really know what to do in terms of tephra disposal/cleanup. They suggested that the provision of timely advice would be useful, in particular to clean up the tephra quickly and keep it out of drains. They noted that once the tephra enters drains it is difficult to remove as normal hosing treatment does not work well. It is much better to keep as much tephra as possible out of wastewater treatment systems. The company also noted that the cleanup was hindered by poor record-keeping; there were not good plans showing affected areas.

The company did not think it worthwhile to invest in specialised equipment or design for an event that occurs once every few decades in Guatemala City, despite the high level of vulnerability of the hundreds of small, open wastewater treatment plants in the city.

3.4 Healthcare systems and services

This section gives an overview of the structure of the healthcare system in Guatemala, impacts of the eruption gained from visiting healthcare centres in Guatemala City, and a summary of the response actions taken. This report provides only the preliminary findings of this study. Further analysis of the interviews and data is ongoing.

3.4.1 Background on healthcare system in Guatemala

The health sector is comprised of both public and private institutions as well as a large traditional medicine sector. The public health system supports about 25% of the population, the private sector serves 10%, the Guatemalan Social Security Institute (IGSS) supports 17%, and NGOs meet the needs of 2.5% of the population in Guatemala (PAHO, 2001). The remainder of the country's population (over 40%) do not receive any form of healthcare coverage (PAHO, 2001). In 2001 the annual spend on public health, as a proportion of GDP, was 5.4% (PAHO, 2001).

However, a verbal account given by the Ministry of Health provided different statistics from the PAHO (2001) results. As the PAHO (2001) figures have not been updated since the report was published (2001) and since we are unable to validate either sources, both sets of information have been included to ensure complete reporting of the data collected on this trip. According to the Ministry of Public Health, 3-4% of the population are treated by private health institutes, 12% are covered by Social Security (which covers people who work and pay taxes), and 10-15% of the population are not covered by the health system (they have their own community system, called 'traditional medicine', which is a mixture of religion, health, cultural, social, and anthropological influences). Health coverage is not universal as the public health system would have to cover the remaining population (around 70-75%), but only 0.9-1% of the national GDP is spent on health (Ministry of Heath epidemiologist). The Ministry of Health epidemiologist estimated that the national expenditure on public health should be around 4-5% of GDP (New Zealand spends 8.1% GDP on healthcare as a comparison (OECD, 2003)), which results in permanent shortages in resources (Ministry of Heath epidemiologist). Additionally many people do not have access to the health system. Guatemala has a large indigenous population (around 45% of the total population), and a large percentage of people living in poverty and also in rural areas, far away from health centres which are usually only open Monday to Friday from 8 am to 4:30 pm (Ministry of Heath epidemiologist).

The health sector underwent economic reform in 1994, and of the government budget given to the municipalities, 90% is supposed to be spent on education, health, infrastructure and public services (PAHO, 2001). Further improvement of the health sector was incorporated into health policies for 1996-2000, including increasing health coverage and the quality of health services. To deal with the lack of healthcare coverage to the population, a Comprehensive Health Care System was designed, aimed at using volunteers and community participants to bring healthcare services to the entire population (PAHO, 2001).

The community-based health delivery service is structured as follows. There are 1500 centres in total, stepping down in size and facilities from hospitals to municipal health centres (doctors, nurses, technicians) to health posts in villages (midwives and auxiliary nurses) to local ‘centres of convergence’ (community health workers, visited once monthly by medics). Depending on the severity of the illness, patients are moved upwards through the system or transferred as necessary.

However, the healthcare system is still largely centralised in Guatemala, with three large public hospitals and most of the healthcare resources and services located in Guatemala City (Ministry of Health epidemiologist). There are 43 public hospitals in the whole country, generally one in each department (province). However staffing and equipment shortages are problematic, and are not sufficient to meet the health needs of the country (Ministry of Health epidemiologist). There is also very little communication and coordination between the various facets of healthcare in general (e.g. public, social security, private, community care) (Ministry of Heath epidemiologist). But in an emergency situation by law, Guatemala has a national commission for disaster relief (CONRED), which is the national representative of all institutions in a state, whether public or private.

Staffing and equipment shortages and lack of financial resources are persistent problems in the healthcare system, which struggles to meet the needs of the population. Dengue fever is the major public health problem in Guatemala (Ministry of Health epidemiologist). It became epidemic in 2009 and cases continued to increase in 2010. At the national level, pneumonia is the primary cause of death in Guatemala.

3.4.2 Healthcare response to eruption

Normal service at health centres is Monday to Friday, 08h00 to 16h30. The Ministry of Public Health’s response to tephra fall was to increase service at health centres to 24 hours a day, and to set up *albergues* (shelters), to provide health services to outpatients and for surveillance. Medical staff visits the shelters once or twice a day and write a daily report that is circulated among the government authorities. In parallel to this, the Emergency Committee also runs 24 hours a day, 7 days a week during the emergency period, based at the Ministry of Public Health. No additional resources were available to cover this increase in service, and so there was no relief cover for shifts (Ministry of Heath epidemiologist).

Informal discussions with a local farmer in the village of San Francisco de Sales revealed that the public health department arrived in the area 1-2 months after the eruption, and installed a temporary clinic which remained for eight days.

The epidemiologist at hospital A also discussed the shelters, and said that they were set up in affected areas. Their capacity was generally insufficient, which resulted in overcrowding, and the shelters themselves were supplied with only improvised basic services such as potable water. As a result of the overcrowding and communal living, the HIV programme also distributed condoms in the shelters. Multi-disciplinary teams visited the shelters, comprised of nurses, doctors, psychologists, environmental health inspectors and social workers (hospital A epidemiologist).

3.4.3 Impacts of the eruption on public health

During fieldwork, interviews were undertaken in two large public hospitals in Guatemala City and also with a senior official within the Ministry of Health. In general, the hospitals reported high patient attendance at all times, and an inability to cope with levels of demand under normal circumstances.

3.4.3.1 Ministry of Public Health experience

According to the Ministry of Public Health there is no data to support a direct link between respiratory effects and the tephra fall. The Ministry of Health epidemiologist informed us that San Carlos University had undertaken an analysis and found that there was no impact on the health of the population from the tephra fall. However, this study was unavailable to us. Two tephra samples were sent to Durham University (UK) by Professor Bill Rose, of Michigan Technological University (USA). A summary of the results (reproduced here with the kind permission of Dr Claire Horwell) is included in Appendix 6. The tephra deposited in Guatemala City was described by many interviewees as being ‘sandy’, and this is borne out by the grain size analyses which show no material in the <63 μm size fraction, and therefore not in the respirable size fraction (<4 um). Overall, the lack of respiratory effects caused by the tephra fall is probably due to a range of factors: the coarse grain size of the tephra, the rainy conditions during the eruption, which dampened down the deposited tephra, and the fact the eruption occurred in the evening when people were generally indoors.

It should also be noted that any association between the event and impacts on public health would probably be difficult to detect because of the general lack of documentation and reporting of health cases in Guatemala, and the normal seasonal trends in respiratory diseases which may make it more difficult to detect impacts. However, there was apparently a small reduction in dengue fever cases during the period of the eruption and tropical storm (Ministry of Health epidemiologist) which could have been due to the heavy rains cleaning out mosquito breeding grounds.

The hospital epidemiologist also discussed the local crop damage from tephra fall, which led to food shortages and said that in the future this may result in cases of undernourishment as a long-term impact.

3.4.3.2 Public hospital experience

Interviews were conducted with staff at two of the three large public hospitals in Guatemala City (referred to hereafter, to protect participants’ privacy, as ‘hospital A’ and ‘hospital B’). Regions closer to the volcano also suffered a range of effects on public health, but within our brief visit we were unable to visit other health centres. Some data on civil defence aspects of the eruption is presented in Section 5.3.1.

We were fortunate to be given a database of statistics on hospital Admissions to the adult emergency department of hospital A during the period immediately after the tephra fall (28 May – 7 June 2010), with cases specifically associated with either the Pacaya eruption or the tropical storm (Appendix 5). A total of 74 cases caused by these two natural disasters were recorded during this time period, including two deaths due to traumatic brain injury. Both deaths were caused by falls from roofs while cleaning tephra (hospital A epidemiologist). Overall, 69 admissions were related to the eruption and the remaining five to the tropical storm. The diagnoses were divided into broad categories and broken down by gender (Figure 3.9). For the time period 31 May – 7 June, a greater level of detail was available about the causes of admissions related to the eruption and tropical storm (Table 3.2).

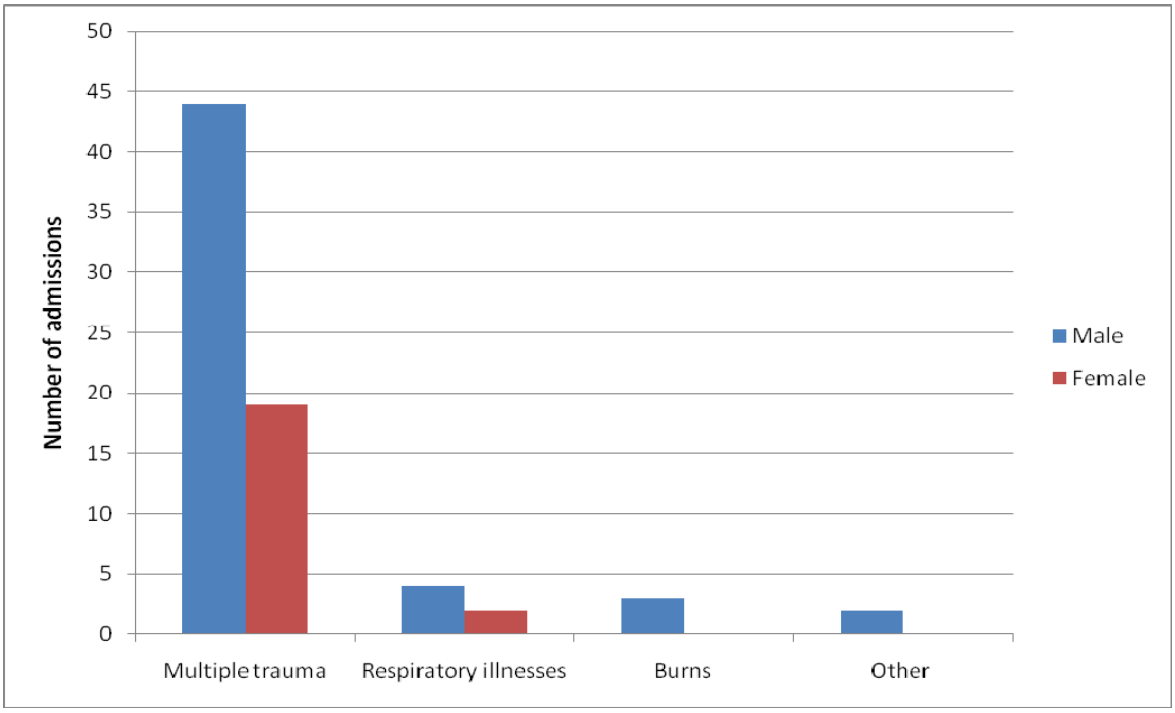


Figure 3.9 Admissions to adult emergency department at hospital A, by gender and diagnosis, during period 28 May-7 June 2010, specifically related to natural disasters (the Pacaya eruption or tropical storm Agatha) (n=74).

Of the total 74 admissions related specifically to the eruption or tropical storm (Figure 3.9), the majority of cases were categorised as 'multiple trauma' (63 cases, or 85%). These were mostly fractures, with smaller numbers of dislocations and cases of severe bruising, from a range of causes including falling from roofs, other falls and traffic accidents (Table 3.2). There were six cases (8%) of respiratory illness, including asthma and pharyngitis, and three cases (4%) of burns, with two being from high voltage lines and one from being struck by an incandescent ballistic bomb (this person also suffered multiple trauma).

Table 3.2 Causes of injury and illness among admissions to adult emergency department at hospital A, 31 May-7 June 2010 (n=22).

Event and diagnosis	Number of cases	%	Comments
Fall from roof – multiple trauma	9	41	Cleaning tephra from roofs and gutters
Fall (unspecified) – multiple trauma	7	32	
Traffic accident – multiple trauma	2	9	Vehicle slid on tephra
Respiratory problems	4	18	Asthmatic crisis, pharyngitis, two workers exposed to gas leak while underground

Thus, multiple trauma was the most common 'indirect' impact recorded in Guatemala City, with men twice as likely to be admitted to the Emergency Department as women (Figure 3.9). The low incidence of respiratory disease is consistent with factors described in Section 3.4.2.1. While only partial data is available on specific causes of accidents, the data presented in Table 3.2 suggests that falls from roofs and other heights were primarily responsible.

Staff at hospital A reported that the main demands for services as a result of the eruption were in the Operating Room (OR) and the trauma unit. The hospital did not discern an increase in respiratory cases as a consequence of the tephra fall; however any increase may have been masked by a natural wintertime increase in acute respiratory cases. Staff generally concurred with the Ministry of Health assessment that the exposure of the city's population to the tephra fall was generally low because it occurred at night time, and also was raining. Staff had expected an increase in respiratory cases and conjunctivitis, and cases related to water contamination, but these did not materialise.

At hospital B, a doctor offered the opinion that this hospital would probably have received fewer cases related to the eruption due to its location in the north of the city, which was less severely affected than the south (Figure 2.8). Unlike hospital A, this hospital did not record admission data in relation to impacts of the eruption and tropical storm. However there were some trauma injury cases admitted to the hospital, which apparently were caused primarily by falls from roofs, through roofs or from other heights as the cleanup began. A further issue was complaints of back pain, particularly among the elderly, caused by sweeping up or shovelling the heavy tephra. Overall, the eruption did not cause a discernible increase in patient numbers and no additional staff resources were required aside from those required for cleanup operations (see Section 3.4.4).

In terms of affected services at hospital B, staff had already arrived at the hospital for the shift change at 19h00, which was prior to the heaviest tephra fall thus there were no issues with staff being able to get to work. The next day the tephra fall was lighter and did not cause significant access problems for hospital staff (hospital B maintenance staff). However, the tephra fall on the hospital's roofs required many members of staff to assist on the first day of cleanup, which meant that few services (other than emergencies) were offered at the hospital on this day.

3.4.3.3 *Experiences of the public*

A farmer in San Francisco de Sales told us that, in his experience, the eruption caused an increased incidence of diarrhoea, respiratory and psychological problems in the local population. The timings of these impacts were not discussed and so the cause of diarrhoea is uncertain. The farmer added that he still has dreams about the event. He also said that masks were sent for the population but were not given out for free, and so most people did not purchase and wear them.

3.4.4 Buildings, equipment and infrastructure

Hospital A is located close to the drainage divide that runs in an approximately NW-SE direction across Guatemala City. This hospital is over 50 years old, and pipework is suffering from scale deposition problems, with sumps and tanks regularly backing up and overflowing, as well as the underlying drainage network being old, chaotic and poorly maintained. The tephra fall exacerbated this hospital's pre-existing drainage problems. The deposited tephra was washed into drains where it caused further blockages and flooding. Basements flooded and three water pumps were ruined so that the hospital was reduced to using one emergency water pump. Gutters also became blocked with tephra, causing flooding in through ceilings. The cleanup of tephra from the hospital roof also caused abrasion damage to a waterproof coating on the roof, which added further to leakage problems.

Some other impacts to hospital buildings, and effective mitigation measures were also reported:

- Other problems at Hospital A included the blocking of air conditioning filters by tephra. Water tanks were covered, and so were unaffected by tephra deposition. The hospital did not suffer any power loss as a result of the eruption, and has its own back-up power source that starts automatically when there is an outage. Although power cuts did occur city-wide, lasting for approximately three hours, the hospital had sufficient back-up generation capacity to cope for this length of time.
- Mats were placed on the floors at entrance points, to prevent slipping and to prevent tephra from being trampled further into the hospital. There are restricted areas for surgery, paediatrics and emergency procedures, away from normal foot traffic areas. In these areas, staff are required to change their clothing and clean the wheels on gurneys before wheeling them through. As a result of these normal routines, these sensitive areas remained free of contamination from tephra.
- Tephra was trampled into Hospital B by the flow of people, so cardboard was placed at entrances to the building to mitigate this problem (hospital director). Despite this measure, internal flooring was noticeably abraded by tephra (hospital maintenance staff). As with Hospital A, the normal routines of the doctors, such as changing their clothes before accessing restricted areas, prevented tephra ingress issues in sensitive units (hospital maintenance staff). At the time there was an increased demand for the pulmonary ventilators (artificial respirators), and the hospital has had to rent additional equipment, but this demand is typical for that time of year so cannot be attributed to the eruption (hospital doctor).
- Hospital B is located in the northern part of the city, and suffered a different range of problems than Hospital A. This hospital was in the process of painting a waterproof coating onto its roofs to prevent leakage when the eruption happened. This coating was

damaged in some areas during the cleanup operations as the tephra was extremely abrasive (described in Section 3.4.4, and shown in Figure 3.11). However, flooding was not a serious issue for this hospital as it was for Hospital A.

- Air conditioning units on the second floor, which are specifically for the operating rooms, became blocked by tephra and required cleaning, but were undamaged (hospital director). The hospital has its own covered water tanks for water supply, and these were unaffected by the tephra, and this hospital did not suffer power loss during any part of the eruption. The tephra fall alone did not have significant effects on transport to and from the hospital or around the city, but the tropical storm did add to the city's transport problems as it washed the tephra into drains and created widespread surface flooding (see Section 3.5.1).

3.4.5 Cleanup operations

Hospital A did not make specific comments about the demands of the cleanup operations following the tephra fall, but did note that flooded basements required cleaning out.

The extensive roofs of hospital B (an estimated 10,000 m^2, hospital maintenance staff) were covered in 2-3 cm coarse tephra. These roofs are largely flat, and thus tephra was not washed off. The rainfall received mostly served to dampen the tephra. The quantity of wet tephra involved meant that the cleanup was too major for the normal cleaning team. On the following day, all available staff were assigned to help with the cleanup and a further 25 Army personnel were also brought in to help (hospital maintenance staff). Internal cleaning was also suspended to focus on the external cleanup; as a result two additional cleaners were hired for a month afterwards to assist with internal cleaning.

Cleanup efforts were directed towards the roofs, to prevent further rains from washing it into drainpipes and blocking them. It took three to four days to clear tephra from the roof. Maintenance staff kindly provided us with photos of the cleanup (Figures 3.10 and 3.11).

Figure 3.10 Roof of hospital B covered in tephra.

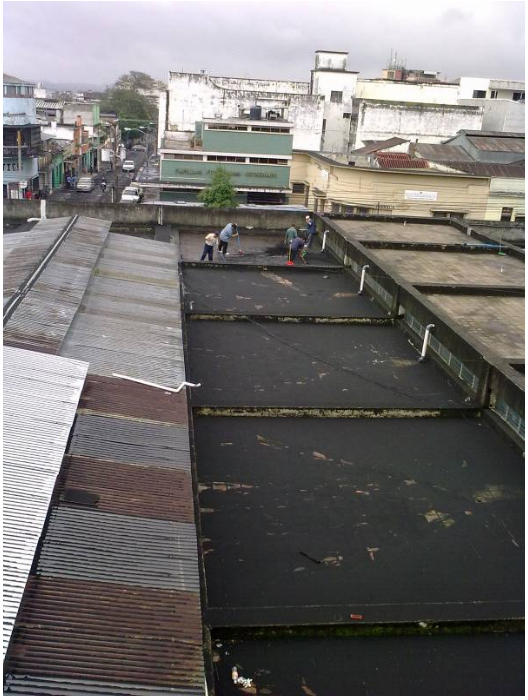



Figure 3.11 Cleanup of tephra from roof in progress (left), and abrasion damage to surface coating on roof (right).

3.4.6 Financing issues

At hospital A there is a committee for the disposal of solid hospital waste and for facilitating the emergency management of the hospital. The committee organises the priorities for funding investment in the hospital and is comprised of the epidemiological department, the risk management department and the maintenance department. However, the financial office itself allocates the funds and has the final say on investment (hospital A epidemiologist). The Strategic Planning Unit is external to the hospital at the level of the Ministry, who verify and approve the infrastructure projects presented by the state institutions (hospital A worker). At the time of the eruption the hospital budget was in deficit, and so the additional costs associated with the emergency and the demand on resources exacerbated this situation. As a result, the financing issues and liquidity of the hospital hindered their capabilities and the response.

The risk management committee at hospital A has a 'disaster room' for emergencies, which is a virtual environment for anticipating the supplies that may be needed in an emergency (hospital A epidemiologist). There is a risk management manual, which is the hospital's integral plan for any type of disaster. In the hospital manual there are plans for evacuation, mitigating fires, and a sanitation plan, but no plans specifically related to volcanic eruptions. There is a risk management plan, relating to internal hospital risks (such as the hospital's infrastructure), and the intention is to integrate the risk management and emergency manual plans so that they work together. However, this is difficult to achieve in practice because there is no one solely dedicated to risk management at the hospital. The risk management committee all have hospital day jobs to attend to, and since normal work is continuing at the hospital it is difficult to make progress on the plans (hospital A doctor). The missing element is putting the existing plans into practice (hospital A worker). Externally, there is a Ministry of Health plan for treating patients relating to volcanic eruptions, but this is separate from the hospital manual.

In terms of hospital emergency management at hospital B, there is a risk management committee. When the tephra fall happened the committee met and this resulted in getting the army to help with the cleanup. In general the hospital emergency plan is medical emergency-focussed, rather than disaster-focussed and does not include volcanic eruptions (hospital B doctor).

The investment required for maintaining and upgrading infrastructure (e.g. for drainage) has no allocated budget from the Ministry, and so this has to come out of the operating budget (hospital B doctor). There is also no policy for construction to mitigate disasters (for example for seismic design), and construction standards in Guatemala are poor, even for hospitals (hospital B doctor).

There is emergency funding available from the government that was provided by international donors and ECLAC. However, the funding is difficult to obtain, as hospitals must provide documentation of their needs to apply for funding through CONRED and the government. They must prove their need through statistics, photos and documentation. Some of the effects are hard to prove, such as over-demand on certain components resulting from the damage to others. This process also typically takes too long to be useful (hospital B doctor).

3.4.7 Summary

Data on admissions (specifically attributable to either the volcanic eruption or the tropical storm) to the adult emergency department for the period 28 May -7 June 2010 was obtained from one of the two main public hospitals in Guatemala City. A total of 74 cases were seen by the ED during this period, of which 69 were related to the eruption and five to the tropical storm. Two deaths were recorded. The majority (85%) of cases were categorised as ‘multiple trauma’ from a range of causes including falling from roofs, other falls and traffic accidents. There were more minor incidences of respiratory illnesses and burns. However, compared to normal demands on healthcare services, these numbers are small.

Overall, the direct effects of the 2010 tephra fall event on hospitals appeared minimal. Any increase in demand on services was too minor to be distinguishable from normal seasonal trends. There was little tephra ingress into buildings and the tephra fall was generally viewed by hospital staff as a single event that had to be cleaned up to resume operations. For hospital A, the tephra fall exacerbated pre-existing drainage problems and led to flooding of basements, which required extra effort to cleanup. For hospital B, cleanup of tephra deposited on the roof required extra assistance from the Army. The continuity of critical infrastructure services was not a problem for either hospital, with water supplies covered and unaffected by the tephra fall, and backup generators providing continuous power during power outages. The tephra fall did cause widespread disruption to the city’s transport networks, particularly when it was washed into drains and caused widespread surface flooding. The extent to which this affected access to and from these hospital is not known.

In general the health system is hindered in its response to emergency events by being chronically under-resourced on a permanent basis. Within the country context, it is not surprising that tephra fall is perceived to be a relatively minor problem for healthcare, given its relative rarity, and given the chronic social and economic constraints, together with epidemic dengue fever occurrence in 2009-10.

3.5 Transport networks and the municipal cleanup

3.5.1 Disposal and possible re-use of tephra

This section summarises the findings on impacts on transport networks obtained from interviews with staff from the municipality of Guatemala City, and DGAC (Direccion General de Aeronautica Civil, or Civil Aviation, who manage the international airport).

3.5.2 Impacts on roads and the municipal cleanup

Between 2-3 cm of tephra was deposited on Guatemala City during the paroxysmal eruption of Pacaya volcano on 27 May 2010. The nature of the tephra fall varied across the city, with the southern part receiving greater thicknesses of coarser, sand-sized tephra (Figures 2.7, 3.12, 3.13) while the northern part received lesser amounts of finer tephra.

As the city generates 70 percent of Guatemala's GNP, there was a strong motivation to initiate a prompt and efficient city-wide cleanup to enable critical transport lifelines to be restored as quickly as possible. The cleanup was organised by the municipality, and was initiated on the night of the first tephra fall (27 May). All available municipality staff, from the mayor to the administrative staff, were involved, along with additional personnel from the army. The total quantity of tephra deposited on the city was estimated to be 11,350,000 m^3, and 2,100 km of roads required cleaning.

Figure 3.12 Coarse, sand-sized basaltic tephra covering a paved area in Guatemala City. (photo: Gustavo Chigna, INSIVUMEH).

Figure 3.13 Coarse, sand-sized basaltic tephra covering vehicle (photo: Gustavo Chigna, INSIVUMEH).

For the cleanup, the municipality utilised a pre-existing earthquake emergency plan, which had been drawn up as a local response to the devastating earthquakes in Haiti and Chile earlier in 2010. This plan contained provisions such as arrangements with contractors to supply heavy machinery. It also set up a clear command structure with four levels in a pyramid structure: at the top the mayor, then 14 district mayors, then 54 delegates, then 760 local committees.

As well as the ready access to heavy machinery, another factor in the success of the cleanup was the clear communication with the public. The public were instructed to clear tephra from their own properties (roofs and yards), and to pile the bags up on the street frontage or to take them to designated collection points. Collection bags were donated by sugar and cement companies. Streets were cleaned with street sweepers or by people using brooms and shovels. The tephra was loaded onto lorries either by hand or using small excavators. The cost of heavy machinery hire is shown in Table 3.1, and photos illustrating the cleanup operations are shown in Figure 3.14. The cleanup lasted three weeks.

Table 3.3 Costs of heavy machinery hire for cleanup (Data: Director of Works, Municipality of Guatemala).

<table>
<tr><th>Description</th><th>Quantity hired</th><th>Cost</th></tr>
<tr><td>Trucks</td><td>128</td><td>Q1,246,000</td></tr>
<tr><td>Excavators</td><td>8</td><td rowspan="2">Q400,000</td></tr>
<tr><td>Bobcats</td><td>9</td></tr>
<tr><td>Total</td><td></td><td>Q1,646,000*</td></tr>
</table>

*Approximately $US 0.2 million, converted from Guatemalan quetzales (Q)

Figure 3.14 Cleanup of Guatemala City (photos: Director of Works, Municipality of Guatemala City and Gustavo Chigna, INSIVUMEH).

The tephra posed a traction hazard for drivers. One interviewee reported that during the evening of the 27 May, it was very hard to drive to his home 12 km away from the airport due to the poor visibility and the slippery surface. His impression was that driving conditions would have been even worse if it had not been raining, as the rain helped consolidate the fallen tephra. Staff at Roosevelt Hospital reported a higher than usual incidence of trauma due to traffic accidents at this time (see Table 3.2). Motorists were also advised by local authorities not to use their windscreen wipers due to the abrasive nature of the tephra. However, the Director of Works of the Municipality reported that the tephra caused few problems for street sweeping equipment, other than normal wear and tear, and that the tephra did not generally cause problems for vehicles as it was cleared quickly and then the heavy rains washed it off the streets.

While fresh volcanic tephra can be corrosive due to its typically acidic surface coating, corrosion was not a widely reported problem after this eruption. An INSIVUMEH staff member reported that on some vehicles, paint blisters corresponding to the position of individual tephra particles formed, including on his own vehicle. However, we did not see any photos of this phenomenon, and corrosion was not mentioned as being a problem associated with the tephra fall by the Director of Works at the municipality, or by hospital maintenance staff. Heavy rains that followed the tephra fall probably would have acted to dilute and flush any initial surface acidity.

The tephra was removed to landfill sites on the edge of the city, and at the time of our visit, tests were being conducted by Mapreco to determine whether the tephra could be suitable for any forms of beneficial re-use. Initial results were not promising (Appendix 3), with the tephra being too friable (lacking mechanical strength) for use as an aggregate. The Director of Works reported that the tephra was ‘not chemically suitable’ but he did not have further information on this. The Director also noted that from their perspective there was an information gap on possible reuses for the tephra, and that any information from international case studies would be very helpful to them. Chemical testing of the tephra was reportedly also carried out by American Airlines, who concluded that the tephra was not acidic (Airport Manager).

While the heavy rains that followed the tephra fall did wash the tephra from the streets, tephra then blocked drains all over the city, and widespread surface flooding occurred (Figure 3.15). The tropical storm, described briefly in Section 2.4, caused serious flooding on a wide scale across Guatemala. The civil defence impacts caused by this storm can be seen as Appendix 3 to this report. In Guatemala City, surface flooding was widespread, with underpasses being particularly affected.

The Director of Works acknowledged that the blocked drains have caused continual flooding problems since the eruption. There have been incidences of flooding in areas that have not previously flooded, and existing flood-prone areas have become worse. During our field visit, heavy rains caused surface flooding, and caused an underpass to flood and become impassable (Figure 3.16). The municipality would like to be able to clean out the drains but currently lack the funds.

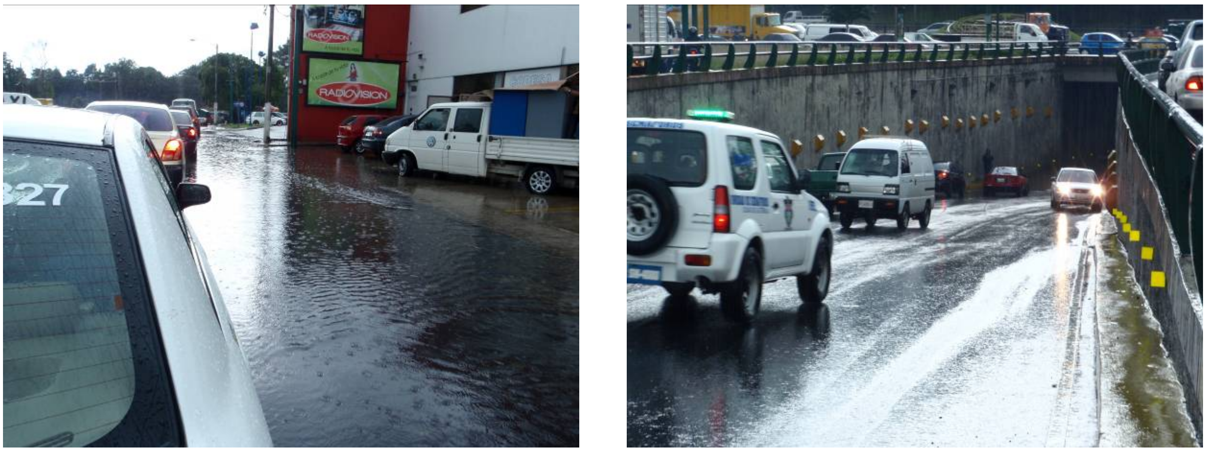


Figure 3.15 On left, surface flooding in Guatemala City; on right, an underpass is closed in heavy rains (both in September 2010).

Figure 3.16 Flooded underpass, Guatemala City, early June 2010 (photo: Director of Works, Guatemala City municipality).

3.5.3 Impacts on El Cedro-San Francisco de Sales road

The road linking the small settlements of El Cedro and San Francisco de Sales (Figure 1.3) received approximately 20 cm of tephra fall, ranging in size from sand-sized up to approximately 3 cm diameter. According to a local guide in San Francisco de Sales, there was no vehicle access to the town on the day after the eruption as the road was too slippery. The road was not cleared, but eventually the surface compacted down and a new road surface was formed on top of the tephra layer (Figure 3.17).

Figure 3.17 Road to San Francisco de Sales, showing compacted tephra road surface.

3.5.4 Impacts on La Aurora International Airport

Guatemala City's international airport (La Aurora) received its first warning of impending tephra fall at 18h30 on 27 May 2010. The warning came from American Airlines staff in Dallas Fort Worth, who had seen the tephra plume on satellite images, and were worried about two AA flights due to arrive at La Aurora at the time. The flights arrived approximately 5-10 minutes prior to the arrival of the tephra plume, and were immediately grounded (Figure 3.18). Airport staff also received a phone call around 19h00 from a colleague in Villa Canales, located approximately halfway between Pacaya volcano and Guatemala City, who reported that it was 'raining sand'. The airport was officially closed at 19h23 the same evening, and re-opened at 13h18 on 1 June (Airport Manager, Direccion General de Aeronautica Civil).

Figure 3.18 American Airlines flight at La Aurora airport following eruption of Pacaya volcano (photo: Gustavo Chigna, INSIVUMEH).

Approximately 2-3 cm of coarse basaltic tephra fell on La Aurora airport. The main reason for the airport closure was to allow for cleanup of the airport, rather than because of airborne tephra hazards to aircraft (which was limited by the short duration of the tephra fall). There was also a high level of concern about the impacts of remobilised tephra on jet engines.

The cleanup began shortly after the airport closure, at 20h00. However, progress was slow during the first night due to a lack of equipment. The personnel requirements for the cleanup were 30 staff from DGAC plus an additional 500 staff loaned by the army and air force. A staged cleanup of the runway and apron involved firstly using bulldozers and graders to scrape tephra into piles which they then shovelled into trucks and removed to an on-site storage location. In an attempt to prevent damage during the cleanup, areas were designated to be cleaned manually, or using the heavy machinery. For instance, manual cleaning was carried out around runway lights. An estimated 56,000 m^3 of tephra was removed from the runway and apron. Finer tephra left behind after the initial cleaning was further cleaned up using either manual sweeping or with street sweepers, and finally, air compressors were used to blow away any remaining tephra. The heavy rains helped wash away the tephra and suppress remobilisation, but made conditions for the cleanup workers miserable.

During the airport closure, military flights continued to operate out of the airport delivering aid to communities affected by the tropical storm. It was a complex task coordinating the cleanup and the military flight schedule.

Tephra was deposited in the grass surrounding the runways, but did not kill the grass. Airport management have let the grass grow longer and are hoping the tephra will be washed into the soil over time. They remain concerned about the potential for remobilisation of tephra from this source, possibly re-contaminating the runway, in windy conditions.

The new bituminous runway surface (which cost $1.7 million USD in December 2009) was destroyed by abrasion damage caused by the cleanup. Markings on the runway and apron were also severely damaged by abrasion and had to be completely repainted before the airport could re-open.

Costs of the airport closure were estimated to be $250,000 USD in loss of income to businesses based at the airport. The airport buildings were also damaged by the tephra fall. Gutters and downpipes were clogged with tephra and caused leaks in the ceiling which were continuing some four months later, and the paint coating on the roof suffered abrasion damage. Tephra did enter the airport terminal buildings through being trampled inside, but did not cause particular problems. Some problems were experienced with the operation of air bridges and software malfunctioning.

3.6 Telecommunications

Physical impacts of tephra on telecommunication systems were not observed first-hand on this trip. However, EEGSA reported very high frequency (VHF) radio interference between substations during the 27 May tephra fall. This primarily occurred south of Guatemala City, particularly to those substations close to the Volcano such as Laguna, Mayan Golf and San Miguel Petapa (Figure 3.5).

Images acquired from INSIVUMEH show a collapsed telecommunications tower in the area of Cerro Chino (see Figure 1.3 for location) due to ballistics (Figure 3.19).

Figure 3.19 A radio communications tower on Cerro Chino that buckled from ballistic and block impacts (photo: Gustavo Chigna, INSIVUMEH).

4.0 IMPACTS ON AGRICULTURE AND RURAL COMMUNITIES

This section summarises the findings from interviews conducted during a brief field visit to the community and surrounds of San Francisco de Sales, located approximately 3 km from the active vent of Pacaya volcano (Figure 3.1). Interviewees were a local tour guide, a resident and a farmer.

4.1 Background

Guatemala's economy is heavily dependent on the nation's agricultural produce. According to the Nation's Encyclopaedia (2010), agriculture contributes about 23% of Guatemala's GDP, makes up 75% of export earnings, and employs 50% of the labour force.

Approximately 9000 people live in communities close to Pacaya volcano, within 5 km of the active cone (Section 1.4.3). The area is primarily a subsistence economy and produce is consumed locally. The main crops in the area are maize, beans and avocadoes, coffee, bananas and peaches.

4.2 Impacts on crops

Up to 20 cm of coarse-grained lapilli fell on San Francisco de Sales and Calderas. After compaction, tephra deposits were approximately 10-12 cm thick at the time of our visit (Figure 4.1).

Figure 4.1 Ground cover of coarse lapilli (tephra layer is ~10 cm thick), San Francisco de Sales, 19/9/2011).

The lapilli fall caused extensive damage to crops in this region (Figure 4.2). The area also received larger ballistic clasts (lower right of Figure 4.2), some of them incandescent. The local farmer reported that crops suffered both crush damage and burn damage. There may also have been acid damage but no further information was available on this topic. No crops could be harvested after the 27 May eruption.

Figure 4.2 Farmer surveys his damaged maize crops, San Francisco de Sales (19/9/2011).

Further north around Lago Amatitlan (Figure 1.2), approximately 15 cm 'hot tephra' was received. There were significant effects on crops, with extensive burn damage (Gustavo Chigna, INSIVUMEH).

As this area is primarily subsistence agriculture, the heavy damage to crops caused local food shortages. The farmer we interviewed reported that his own family suffered hardship and that this was widespread in the district. Both Guatemalan and international aid agencies provided assistance in the form of food supplies and building materials.

4.3 Impacts on livestock

Only limited information on impacts on livestock was collected. Livestock in the area include cows, horses and poultry. Livestock reportedly had to be evacuated out of the immediate area because of a lack of feed. Some had to be sold, at reduced prices.

4.4 Impacts of the eruption on settlements

As described in Section 2.3.1.2, during the paroxysmal phase of the eruption on 27 May, ballistic clasts were ejected from the vent up to 6-7 km away (INSIVUMEH staff). The settlements of San Francisco de Sales, Calderas ad El Cedro (Figure 1.3), located between 2.5 and 3.5 km north of the vent, all suffered significant damage from ballistics, which reached a maximum size of approximately 25 cm (long axis) in this area. These settlements also received approximately 20 cm tephra fall (Figure 4.3).

Widespread damage was inflicted on roofs in the settlements of Calderas, San Francisco de Sales and El Cedro. Incandescent ballistic clasts larger than 20 cm (long axis) pierced corrugated iron and fibro-cement roofs (Figure 4.3) and set houses on fire. One family told us of having to huddle in a door frame to avoid being harmed by ballistic blocks crashing through their roof. According to INSIVUMEH staff, five houses were burned down, and there would probably have been more widespread fire damage if it had not been raining at the time. Damage varied widely depending on roof type. Concrete slab roofs withstood damage, but metal roofs were highly vulnerable to damage. The condition of roofing metal was also important with older and more corroded roofs being more susceptible to damage (Escobar Wolf, 2011).

While damage to roofs was primarily caused by ballistic impacts, the tephra fall also caused some damage. Some long span roofs collapsed due to tephra loading (Figure 4.4), and gutters and drains became blocked which caused flooding damage to buildings. Overall, approximately 90% of roofs in the town were badly damaged and needed to be replaced. Buildings damaged included the public school, several churches and the Park visitors' centre (Escobar Wolf, 2011). At the time of our visit, building of new roofs was well underway.

Figure 4.3 Ballistic damage to roof, San Francisco de Sales (located approximately 3 km north of the vent). Ballistics in this area reached 25 cm in diameter (long axis) (photo: Gustavo Chigna, INSIVUMEH).

Figure 4.4 Roof collapse due to tephra loading, San Francisco de Sales (photo: Gustavo Chigna, INSIVUMEH).

At the time of our visit, on 19 September 2010, large ballistic clasts of up to approximately 20 cm long axis were still visible (Figure 4.5). While roof repair was underway, several severely damaged roofs remained (Figure 4.6).

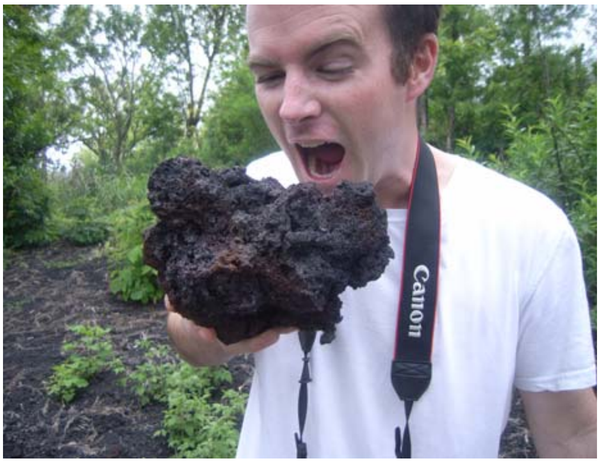


Figure 4.5 Ballistic clasts in vicinity of San Francisco de Sales, 19 September 2010. (approximately 20 cm long axis).

Figure 4.6 Tephra deposition and ballistic damage to roofs, San Francisco de Sales, 19 September 2010.

4.5 Other impacts on rural infrastructure

After the eruption, there were ten days of power outages in the area around the volcano. This was primarily due to ballistic damage to lines and poles, and also treefall onto lines. Some 90% of lines in San Francisco de Sales, El Cedro and Calderas were damaged (Gustavo Chigna, INSIVUMEH). Damage to the road linking El Cedro with San Francisco de Sales and Calderas was described in Section 3.5.2. The arrival of the rainstorm also caused landslides and bridge washouts, which closed the main access road to the volcano for three days. Damage to water supplies was described in Section 3.2.3, and damage to communications equipment in Section 3.6.

5.0 EMERGENCY MANAGEMENT IN GUATEMALA

This section outlines the emergency management structure and the process, problems and lessons learned in emergency management practice. The social response to tephra fall is also included here, with respect to social adaptations developed from tephra fall experience and from increased access to information.

5.1 Volcano monitoring

The monitoring of natural hazards in Guatemala is carried out by INSIVUMEH which is based in Guatemala City. INSIVUMEH monitors all natural hazards including volcanic activity.

INSIVUMEH monitors activity at the three most active volcanoes in Guatemala: Pacaya, Fuego and Santiaguito. There are two seismic stations on Pacaya volcano, four on Fuego and six on Santiaguito. INSIVUMEH also use COSPEC monitoring on all three volcanoes, and DOAS monitoring on Fuego and Santiaguito. There is no permanent observatory for Pacaya volcano, but there is an observatory for Santiaguito in Guatemala (WOVO, 2003).

When activity increases, INSIVUMEH inform the emergency management department, who are the Coordinadora Nacional para la Reducción de Desastres (CONRED, or the National Disaster Reduction Coordinator). INSIVUMEH are the lead agency for hazards. CONRED respond to the information provided by INSIVUMEH, and act at several different levels to manage disasters from the national to local level.

5.2 Emergency management structure

CEPAL (La Comisión Económica para América Latina) [Translated: Economic Commission for Latin America and the Caribbean (English acronym: ECLAC)] is one of the five regional commissions of the United Nations. CEPAL acts as an umbrella agency, under which are regional organisations, and beneath this, each country in Latin America has its own systems for emergency management.

In Guatemala, the Coordination Centre for the Prevention of Natural Disasters in Central America (CEPREDENAC) is the regional agency, which encourages the incorporation of risk management into development. CONRED (National Disaster Reduction Coordinator) is the coordination agency within Guatemala for Disaster Risk Management.

CONRED is traditionally a response organisation, however they are trying to evolve to incorporate preparedness, mitigation and risk management. The emergency management structure is outlined in a chain of local to national level response agencies, as follows:

CONRED - National Level

CODRED - Department [province] Level

COMRED - Municipality Level

COLRED - Local Level

In this disaster reduction structure the municipalities are autonomous and can decide how to subdivide tasks at the local level. As an emergency evolves, the response departments should step-up in stages, from local, to municipal, to departmental, up to the national response level.

In an emergency the municipality manages the sewage, water and rubbish, CONRED provide food and shelter, the police provide security and they all work together on the Emergency Operations Committee.

5.3 Emergency management practice

Emergency management practice has improved over the years, and in particular CONRED and INSUVUMEH have learned to trust each other and work together more closely. This relationship has developed since the 1999 Fuego eruption, when CONRED asked the USA for scientific help, instead of INSIVUMEH. The USA then asked INSIVUMEH for local information on volcanic activity. This process wasted valuable response time. This experience also taught CONRED to trust INSIVUMEH as a scientific organisation (CONRED personnel).

In practice, during emergencies the local COLRED can become overwhelmed and incapacitated, which results in the mid-levels of the emergency management structure becoming bypassed and the response going straight to the national level – CONRED (Ministry of Health official). However, local governments are improving their performance and are now taking on responsibility until their capacity is exceeded.

There have also been difficulties in defining the responsibilities of each agency within the CONRED system, particularly when emergencies transcend municipality boundaries. In these cases, in practice the national level need to respond immediately but the municipal level feel that their authority is being overridden. This is particularly true of volcanic emergencies, as the municipal level does not have local monitoring agencies and the information comes straight from INSIVUMEH to CONRED at the national level (CONRED personnel).

INSIVUMEH have the lead role for hazards, but there are only two volcanologists. In the recent 27 May 2010 eruption, both volcanologists went to locate and monitor activity at Pacaya volcano (from Cerro Chino) while CONRED set up a meeting with decision-makers to start preparations for response (CONRED personnel).

The protocol requires the national government level to contact the local agency (San Vicente Pacaya) to start preparing themselves for an evacuation. They also discuss local capabilities and the local COLRED can request assistance in areas that are lacking. If the municipal level can't find areas to relocate people to in an emergency, then the national government level would step-in.

5.3.1 Emergency management response to the eruption

During our interview CONRED personnel remarked on complications during this volcanic emergency, associated with getting the local authorities to take responsibility and respond to their full capacity.

When tephra fall began to fall in San Vicente Pacaya (15h30-16h00) on the 27 May 2010, the departmental level had already issued road traffic warnings and bulletins by radio and television. A summary of advice contained in CONRED information bulletins is presented in Table 5.1. These bulletins are available from the organisation's website http://conred.gob.gt/

Table 5.1 CONRED information bulletins, 27 May 2010 eruption of Pacaya volcano (information also derived from Escobar Wolf, 2011).

Date (2010)	Bulletin #	Summary
17 May	708	Recommendation to the National Park authority to restrict visitor access to the lava flows.
26 May	726	Eruptive activity increased during the day, generating plumes of 1 km above the vent that dispersed fine tephra onto neighbouring villages. Recommendation made to close access to Park, warn air traffic authorities about risks to aviation.
27 May	729	CONRED began to mobilise staff to villages near volcano around 15h00, to implement pre-emptive evacuation. This was met with some resistance despite fine tephra being dispersed over villages. Seven shelters were prepared in San Vicente Pacaya to accommodate refugees. When the paroxysmal phase of eruption started (after 19h00), evacuation of villages to the west (El Rodeo and El Patrocinio) was already underway, however, tephra and ballistics were dispersed primarily to the north and the villages of El Cedro, San Francisco de Sales and Calderas were the most severely affected.
28 May	731	CONRED declared a Red Alert. As of 12h39, over 1600 people had been evacuated from the villages of San Francisco de Sales, El Rodeo, El Patrocinio, El Cedro, Calderas and Caracolito, to San Vicente Pacaya. Civil Aviation authorities closed La Aurora International Airport due to tephra fall. The Ministry of Education closed schools in Escuintla, Sacatepequez and Guatemala departments. Access to the National Park remained restricted. COMRED was activated in Villa Canales, and set up shelters in the municipal auditorium, a church and the municipal hall, in which 330 people were accommodated. Advice for citizens in managing the tephra fall was also given.
28 May	734	Thus far the eruption had injured 59 people, killed one and prompted the evacuation of nearly 2000.
29 May	748	By this time, a total of 2635 people were in shelters due to the eruption, some 400 houses had been slightly damaged and 375 severely damaged.
27 May 2011	1673	One year on. Summary of civil defence responses to eruption and tropical storm (see Table 5.2)

After 29 May 2010, the attention of the emergency shifted from the eruption to the tropical storm, as both disasters merged into one continuous emergency. A year on from the eruption, CONRED issued a special bulletin to mark the event, which includes final civil defence statistics from both events (Table 5.2).

Clearly, from Table 5.2, the civil defence impacts of the tropical storm were far more severe than the impacts of the eruption. The effects of the storm were also far more widespread (see Figure 2.14) with a quarter of the country's municipalities affected by the tropical storm, whereas the impacts of the Pacaya eruption were quite confined.

Over 100 times more people were affected by the storm, which also caused substantially more fatalities, evacuations, missing persons and damage to homes. The only statistic which is approximately comparable is the number of injuries. The relatively high number of injuries caused by the Pacaya eruption is thought to be due to the fallout of ballistic clasts on the villages immediately north of Pacaya. Although the communities of El Cedro, San Francisco de Sales and Calderas had been partially evacuated before the most intense phase of the eruption, several hundred people may have been directly exposed to the ballistics (Escobar Wolf, 2011).

It is important to note that this is likely to be only a partial data set on the impacts of the eruption and tropical storm; it does not include data on admissions to the emergency departments in major public hospitals in Guatemala City (see Section 3.4.2.3). The impacts summarised in Table 5.2 could be categorised as 'direct' impacts whereas impacts such as injuries sustained while cleaning up ashfalls could be classed as 'indirect'.

Table 5.2 Civil defence data for 27 May 2010 eruption of Pacaya volcano and tropical storm Agatha (data: CONRED Information Bulletin 1673).

Numbers of people	Pacaya eruption	Tropical storm Agatha
Affected	3614	395,291
Evacuated/in public shelters	3093	168,059/111,020
Missing persons	3	37
Injured	59	79
Dead	2	160
Homes damaged	~800	38,000

During our field visit to San Francisco de Sales, we spoke to a local farmer who reported that from the perspective of local people, the evacuation of this area was not particularly smooth. On 27 May the road into the town was difficult to negotiate because of ashfalls. Most people were evacuated on 28 May, to San Vicente Pacaya, where they stayed for 10-15 days. During this time some returned home to tend crops and animals and check houses.

5.3.2 Lessons learned

The Ministry of Health epidemiologist said that for future events, training in environmental risk management was needed for both the authorities and the communities. The last tephra fall in Guatemala City was 20 years ago and so there was a lack of preparedness for this type of event overall. There was an earthquake drill scheduled, for dates that happened to coincide with Tropical Storm Agatha, which the authorities had been preparing since the beginning of the year (a one-time event). The drill plans were modified for the eruption. However, despite this, the response was thought to be inadequate. The response, although modified for an eruption context, also did not take into account multiple events, so when the eruption was followed 24 hours later by Tropical Storm Agatha, the authorities were unprepared.

In general the emergency response in Guatemala is reactive and not proactive, and so preparedness and training is generally not undertaken. We were also told that this is true of annual hazard events, such as heavy rainfall, and so there appears to be a culture of response rather than prevention and preparedness. This is across both communities and the authorities (Ministry of Heath epidemiologist). This situation is further worsened by the chronic lack of resources.

5.4 Public response to volcanic unrest

The last widespread tephra fall (i.e. tephra reported in Guatemala City) was in 1998 from Volcán Santiaguito and resulted in public fear and many people calling INSIVUMEH for advice. However experience of this event meant that people were not as scared during the 2010 tephra fall. Global access to information has also contributed to people being more informed and therefore more relaxed and both INSIVUMEH and CONRED have websites with updated information. Since the 2006 increase of activity at Pacaya there has been increased focus on, and interest in volcanic activity, which has resulted in the population feeling more connected with the hazard and less like it is a remote risk (CONRED personnel).

In the southern areas surrounding Pacaya volcano that are accustomed to receiving tephra fall, the communities were prepared for the 27 May 2010 eruption. But in the northwest they were unused to the hazard and the local government did little to help. The communities had to mobilise and take the lead in the emergency (CONRED personnel). The evacuees did respond to the evacuation and were relocated, although some returned to tend to crops or check on property throughout the period of the evacuation (local farmer).

6.0 DISCUSSION

6.1 Impacts of two natural disasters occurring at once

The arrival of Tropical Storm Agatha immediately after the 27 May 2010 eruption of Pacaya volcano led to a 'complex emergency' (IASC, 1994) in which it is difficult to separate the effects of the individual phenomena (Escobar Wolf, 2011). The impacts of the storm were clearly far more severe in civil defence terms (Table 5.2) for the country as a whole. Most of the impacts of the eruption were confined to a relatively small area immediately north of the volcano, although there was also widespread disruption caused by the tephra fall across Guatemala City, of which the five-day closure of the international airport was probably the most significant. The heavy rains caused severe damage to the country's road networks, including road and bridge washouts and landslides, hampering movement around the country. One consequence of this was that a planned sampling programme of the tephra blanket, by members of the Guatemalan Geological Society, had to be abandoned (Escobar Wolf, pers. comm., 2011). The heavy rains also reworked most of the thinner tephra blanket. As a result there were considerable difficulties in obtaining reliable measurements of tephra thicknesses in distal areas.

Specific ways in which the tropical storm and eruption interacted are discussed in the following sections.

6.1.1 Proximal areas

The towns of El Cedro, San Francisco de Sales and Calderas, located between 2.5 and 3.5 km north of Pacaya's active vent, sustained the most severe damage in the 27 May 2010 eruption. In San Francisco de Sales, an estimated 90% of buildings had their roofs destroyed by ballistic impacts, with more minor impacts from tephra loading. However, just five houses burned down; INSIVUMEH staff commented that it was fortunate that it was raining during the eruption as this almost certainly prevented more fires and may have also prevented fire damage to crops and forests. However, this rain was not specifically part of the tropical storm event. Tephra blocked gutters and drains, and thus probably exacerbated flood damage and surface flooding when the tropical rainstorm did arrive. Although rain can saturate tephra and increase roof loading, this did not appear to be a problem in this town as the tephra was very coarse (Figure 4.1). The combination of tephra deposition and heavy rainfall may have increased the likelihood of debris flows being generated but we do not have any information on this topic.

6.1.2 Electricity networks

At the Amatitlán geothermal plant, the arrival of tropical storm Agatha did not cause any further issues for the plant as staff had already been evacuated and the plant's operations suspended because of the bombardment by volcanic debris. For transmission and distribution lines, the rainy conditions during the eruption added to the flashover risk, and several earth faults occurred. Managers of substations reported that the tropical storm's heavy rainfall washed most equipment clean, with the coarse grain size also contributing to the tephra being easy to remove.

6.1.3 Healthcare services

In Guatemala City, most accidents resulting from the tephra fall requiring admission to hospital were a result of falls from roofs and other heights during cleanup operations, and from traffic accidents (Table 5.2). Traffic accidents reportedly resulted from drivers 'sliding on tephra' (Appendix 5), but it is difficult to establish whether the rainy conditions made the roads more or less hazardous for drivers. The rain probably added to the hazards of cleanup, particularly of roofs. The lack of respiratory effects was a notable feature of this eruption and was thought to be due to several factors: the lack of very fine tephra in health-relevant size fractions, and that people were generally indoors during and immediately after the eruption because it occurred in the evening and was raining at the time. In the days following the eruption, the heavy rains helped dampen down the tephra.

At one of the city's public hospitals, the tephra blocked gutters, drains and sumps, and the heavy rains caused severe flooding problems through ceilings and in basements.

6.1.4 Water supplies

No particular issues associated with the co-occurrence of the eruption and tropical storm were identified for water supplies.

6.1.5 Wastewater

It was a 'double problem' having the tephra fall and the heavy rains, as tephra was washed into storm drains before it could be cleaned up from paved surfaces and disposed of appropriately, and once it was in the drains it became very problematic as it formed intractable and unpumpable masses. Cleaning out drains, sumps and wastewater treatment systems was a major, expensive and time consuming job, and was only partially successful. Although many parts of the city appeared to have pre-existing drainage problems, the residual tephra deposited in underground drainage networks has led to longer term problems, and surface flooding has reportedly worsened in the city since the eruption.

6.1.6 Transport networks

The heavy rains assisted the municipal cleanup by washing tephra from roofs and paved surfaces, but as mentioned above, the tephra was washed into underground drainage networks, which has led to persistent flooding problems.

The lack of reports of corrosion damage to vehicles or roofs following the eruption is very likely due to the heavy rains, which would have washed the surface coating (which can be acidic and contain soluble salts) from the tephra.

For the cleanup operations at the international airport, the heavy rains helped wash away the tephra from the runway and apron, and suppress remobilisation, but made conditions for the cleanup workers miserable. Tephra was deposited in the grass surrounding the runways, but did not kill the grass. Airport management have let the grass grow longer and are hoping the tephra will be washed into the soil over time. They remain concerned about the potential for remobilisation of tephra from this source, possibly re-contaminating the runway, in windy conditions. The heavy rains were helpful at the time in helping bed the tephra into the soil. As for other buildings, the airport buildings' downpipes and gutters were clogged with tephra and caused leaks in the ceiling.

6.2 Lessons for New Zealand

6.2.1 Relevance of 27 May 2010 Pacaya eruption to predicted activity of Auckland Volcanic Field

Auckland is New Zealand's largest urban centre, with over 1.5 million residents. The city lies entirely within the Auckland volcanic field. This field, covering an area of 360 km^2, has over 50 individual eruptive centers of basaltic composition, which have displayed a range of effusive, Strombolian, Hawaiian and phreatomagmatic eruptive styles (Houghton et al. 2006). The eruptions have produced a large number of volcanic cones ranging in radius from 230 to 580 m (average 400 m) and area from 17 to 54 ha together with a lesser number of maars and tuff rings. Each cone formed during episodes of Strombolian and/or Hawaiian fire fountaining commonly accompanied by phreatomagmatic episodes. The largest and most recent eruption formed Rangitoto lava shield less than 800 years ago (Allen and Smith, 1994).

Despite the small size and intensity of Auckland eruptions (typically Strombolian and Hawaiian eruption styles), the risk of proximal flow hazards and tephra fall at longer distances is high because of the high density of buildings and lifelines. Rapid cone growth during future eruptions will define a region of some 30 to 100 ha where complete destruction will occur on a time scale of hours (Houghton et al. 2006). Avoidance and evacuation are the only likely mitigation options. However, for tephra fall in medial and distal locations application of mitigation strategies may reduce potential impacts.

It is thus essential to understand the likely impacts of proximal basaltic tephra fall on a city. The May 2010 eruption of Pacaya volcano, Guatemala, offers a useful analogy to a dry magmatic eruption from the Auckland Volcanic Field.

6.2.2 Planning for multiple hazards

Planning scenarios should take into account that hazard events may not occur in isolation, particularly weather hazards. As described in Section 6.1, heavy rains can modify the impacts of volcanic eruptions, exacerbating some impacts and mitigating others.

6.2.3 Ballistic fallout

Impacts from ballistic block fallout are extremely destructive and dangerous in the event of a VEI 2-3 Strombolian eruption from the Auckland Volcanic Field. The distribution of fallout is typically symmetrical if the eruption is vertically directed, but a directed eruption (such as the 27 May 2010 Pacaya eruption) may result in an asymmetric fallout distribution which may not be well predicted by hazard zone maps based on concentric zones.

Damage to roofs was dependent on two factors. Preliminary data from Escobar Wolf (2011) suggested that fragments larger than 20 cm (long axis) pierced roofs. The roof construction was the other important factor. Concrete slab roofs withstood ballistic fragments in the affected settlements, but metal (corrugated iron) and fibrocement roofs were vulnerable. The condition of metal roofs was also important, with older and more corroded roofs being more vulnerable. Other factors such as the orientation of roof surfaces relative to the volcanic vent may also be important. Secondary fires are also a likely consequence of incandescent ballistic block fall.

The main lesson to be learned from the eruption of Pacaya volcano is that it is vitally important for public safety to establish and enforce an exclusion zone around the vent as there is little that can be done to protect against the destructive properties of ballistic fallout.

6.2.4 Tephra impacts on infrastructure

For impacts on electricity networks, even coarse-grained tephra is capable of increasing flashover potential on electrical insulators (Wardman et al., 2011). Immediate cleaning of substations and transmission and distribution lines is vital to minimise network disruption.

The coarse basaltic tephra deposited across Guatemala City was highly abrasive, and considerable damage was sustained when it was removed from surfaces such as a waterproof coating on a hospital roof and the main runway of the international airport. In the latter case the bituminous coating was destroyed. It may be worthwhile developing methods for cleanup of highly abrasive tephra that will minimise damage (e.g. suction pumps). The tephra was also relatively dense (refer to Appendix 3) which made it difficult to clean out of underground pipework. Remobilisation by wind, which has been a major feature of other eruptions such as the 1991 eruption of Hudson volcano (Wilson et al.,2011b), is unlikely due to the coarse and dense nature of the tephra, although the highly friable tephra may be crushed into smaller fragments which may be more readily remobilised. We recommend that specific guidelines be developed for cleaning coarse, dense tephra. Additionally, it is unlikely this style of eruption will lead to respiratory health hazards, but it still appears to be slippery and the risk of accidents during cleanup is high.

The eruption deposited 2-3 cm tephra across Guatemala City. As the city generates 70 percent of Guatemala’s GNP, there was a strong motivation to initiate a prompt and efficient city-wide cleanup to enable critical transport lifelines to be restored as quickly as possible. The cleanup was organised by the municipality, and was initiated immediately, on the night of 27 May. This cleanup was based on the activation of an emergency plan which was not specific for volcanic tephra, but which had been drawn up as a local response to the devastating earthquakes in Haiti and Chile earlier in 2010. This plan contained provisions such as arrangements with contractors to supply heavy machinery. It also set up a clear command structure with four levels in a pyramid structure: at the top the mayor, then 14 district mayors, then 54 delegates, then 760 local committees. As well as the ready access to heavy machinery, another factor in the success of the cleanup was the clear communication with the public. The public were instructed to clear tephra from their own properties (roofs and yards), and to pile the bags up on the street frontage or to take them to designated collection points. Collection bags were donated by sugar and cement companies. Streets were cleaned with street sweepers or by people using brooms and shovels.

However, despite these efforts, the heavy rains that followed the eruption washed considerable quantities of tephra into the city’s underground drainage networks where it became difficult and intractable to deal with, and continues to cause drainage problems. It is also relevant to note here that modern wastewater treatment plants (such as the Mangere WWTP) are highly vulnerable to tephra ingress through sewer lines, as it will overload equipment designed to trap solid debris. Mechanical pre-screening equipment such as rotating bar screens are highly vulnerable as tephra can abrade moving parts and block screens which can cause motors to burn out (Wilson et al., 2011a). Stormwater and sewage networks are largely separate, but Auckland City has approximately 10% of combined stormwater and sewage lines. Tephra can also enter sewer lines through illegal cross connections (e.g. roof downpipes connected to sewer lines), around manhole covers, and through household gully traps. Even if street cleanup efforts are timely and effective, it is probably still advisable to consider measures such as bypassing treatment plants and discharging untreated sewage (or preferably utilising a holding pond) to avoid doing major damage to treatment plants, given the difficulty in preventing tephra from entering sewer lines.

General recommendations to decrease the vulnerability of infrastructure to volcanic eruptions have been made elsewhere (www.aelg.org.nz) and are not repeated here.

7.0 SUMMARY

The 27 May 2010 eruption of Pacaya volcano began shortly after 14h00. The most violent phase started shortly after 19h00 and lasted approximately 45 minutes. This paroxysmal phase generated a plume that was directed towards the north. At Cerro Chino, 1 km from crater, large ballistic fragments fell (up to -0.5 m long axis) killing one news reporter, injuring many others, and destroying buildings, vehicles and equipment. This took local communities and civil defence by surprise as previous tephra falls had been to the west and southwest of crater and preliminary civil defence efforts were focused on communities located in these areas. Three communities (El Cedro, San Francisco de Sales and Calderas) located 2.5-3.5 km to north of crater were particularly badly affected by the fall of ballistic clasts. Roofs in these towns were extensively damaged by ballistic blocks and to a lesser extent by tephra accumulation. The tephra plume travelled to the north, and Guatemala City was covered in an estimated 2-3 cm of coarse basaltic tephra that was described by local residents as being like ‘black sand’.

Impacts of this event on specific sectors are described under the following headings.

Electricity supply systems

- The only power generation site affected by the 27 May 2010 eruption was ORMAT’s Amatitlán geothermal plant which suffered damage to its roof and condenser fans. Operations were discontinued immediately following the eruption and the plant remained offline for three weeks while repairs were made and tephra was cleaned from equipment and surface gravel.
- No problems occurred for Guatemala’s transmission equipment. However, two of ETCEE’s large substations (220 kV) required cleaning immediately after the tephra fall to prevent tephra-induced failure of the substation apparatus.
- Distribution companies endured many faults on their supply equipment (e.g. lines operating at <69 kV) for several days following the eruption. EEGSA reported multiple flashover events on six medium voltage circuits (69 kV), three of which had to be taken offline despite repeated efforts to reclose the circuits.
- Several EEGSA substations received coarse tephra fallout during the eruption, particularly those substations located south of Guatemala City closest to Pacaya volcano (e.g. Laguna, Mayan Golf and San Miguel Petapa). Cleaning of these substations, scheduled for May 29 and 30 was suspended due to the onset of Tropical Storm Agatha and the combination of heavy rains together with tephra contamination resulted in further electrical faults (flashovers) following the tephra fall out.
- No instances of corrosion, abrasion or increased step-touch potentials at any of the affected transmission or distribution facilities were reported.

Water supplies

- The municipal water company EMPAGUA supplies 85% of Guatemala City’s residents. Its production rate is 4000 L/s.
- The eruption caused several problems for EMPAGUA’s treatment plants. Airborne tephra caused abrasion damage to air-cooled motors and they stopped straight away. Tephra was also deposited in open air tanks, with most settling quickly but some smaller particles remaining in suspension and increasing turbidity. The tephra also affected

groundwater wellhead pumps. Increased cleaning of tephra from EMPAGUA's own substations (used for pumping groundwater) was necessary.

- EMPAGUA opted to clean storage tanks and filters rather than attempt to treat the water. The cleaning operation took three days and affected production rates. However, an erratic water supply is not unusual in Guatemala City, and many residents have adopted adaptive measures such as on-site storage tanks, so disruption to end users was probably minimal.
- The director of EMPAGUA thought that it would be worthwhile covering equipment such as the open storage tanks and groundwater wellhead pumps, to increase resilience in the event of future eruptions.
- In San Francisco de Sales (approximately 3 km north of the vent of Pacaya), the water supply was disrupted for eight days due to ballistic block fall damage to pipework.

Health care systems

- Despite healthcare reform and the development of a community care system, the healthcare service is still largely centralised in Guatemala City rather than available to the whole population. There are generally insufficient healthcare resources in the country to meet the health needs of the population.
- The Ministry was unprepared for a tephra fall and were slow to respond, taking one month to arrive in the most affected area of San Francisco de Sales.
- Data on admissions (specifically attributable to either the volcanic eruption or the tropical storm) to the adult emergency department for the period 28 May -7 June 2010 was obtained from one of the two main public hospitals in Guatemala City. A total of 74 cases were seen by the Emergency Department during this period, of which 69 were related to the eruption and five to the tropical storm. Two deaths were recorded. The majority (85%) of cases were categorised as 'multiple trauma' from a range of causes including falling from roofs, other falls and traffic accidents. There were more minor incidences of respiratory illnesses and burns. However, compared to normal demands on healthcare services, these numbers are small.
- The tephra fall in Guatemala City appeared to have limited impacts on the provision of essential healthcare services.
- The main impacts to hospital infrastructure were caused by blocked drains which caused secondary flooding. This affected some hospital facilities and caused widespread disruption to the city's road network. The incidence of secondary flooding highlights the impacts of inter-related infrastructure and the need to account for interconnected networks when assessing facility functionality.
- Roof clearance of tephra was a priority, and hospital B worked together with the army to clear the hospital roof quickly. Minor effects caused by tephra ingress into hospitals included the need for additional cleaning, abraded flooring, and blocking of air conditioning filters.
- Overall mitigative actions at hospitals prevented tephra ingress and normal hospital procedures prevented further contamination within hospitals. There was no structural damage to either hospital. Back-up generation power and covering water supplies critically prevented problems with hospital operability by ensuring the security of lifelines and preventing cascading impacts to hospital functions.

Transport networks and municipal cleanup

- A prompt and efficient city-wide cleanup was organised by the city's municipality. All available municipality staff, from the mayor to the administrative staff, were involved, along with additional personnel from the army. The cleanup lasted three weeks.

- According to the municipality the total quantity of tephra deposited on the city was estimated to be 11,350,000 m^3, and 2,100 km of roads required cleaning. Clear communication with the public and access to heavy machinery helped to expedite the cleaning process.
- The public were instructed to clear tephra from their own properties and to pile up bags (donated by sugar and cement companies) on the street frontage or to take them to selected collection points.
- Tephra fallout posed traction and abrasion hazards for motorists. However, the tephra caused few problems for street sweeping equipment and did not generally cause problems for vehicles as it was cleared quickly and subsequent heavy rains from tropical storm Agatha washed it off the streets.
- Tephra was removed to landfill sites on the edge of the city. Plans to re-use the tephra for other purposes (e.g. aggregate in concrete production) were abandoned due to the unsuitable properties (e.g. friability) of the tephra.
- Widespread surface flooding occurred across the city due to the blocking of drains by the tephra. This continued for months afterwards.
- Approximately 2-3 cm of coarse basaltic tephra fell on La Aurora airport, requiring the grounding of all aircraft at the time. Closure of the airport occurred at 19h23 on 27 May and was re-opened at 13h18 on 1 June. The main reason for the airport closure was to allow for cleanup of the airport, rather than because of airborne tephra hazards to aircraft. Costs of the airport closure were estimated to be $250,000 USD by loss of income to businesses based at the airport.
- The airport's new bituminous runway surface (which cost $1.7 million USD in December 2009) was destroyed by abrasion damage caused during the cleanup. Markings on the runway and apron were also severely damaged by abrasion and had to be completely repainted before the airport could re-open. Airport buildings were also damaged by the tephra fall where gutters and downpipes were clogged with tephra and caused leaks in the ceiling which were continuing some four months later.

Telecommunications

- VHF radio attenuation was reported by EEGSA's substations located south of Guatemala City, especially those close to the volcano.
- Photos acquired from INSIVUMEH indicate ballistic damage to telecommunication towers located close to the volcano (Cerro Chino).

Impacts on proximal communities

- Main crops in the rural settlements surrounding Pacaya volcano include maize, coffee, beans, bananas and avocados. All agricultural produce in the area immediately to the north of the volcano was lost to the 27 May 2010 eruption. As it is largely a subsistence economy, local food shortages resulted.
- There was major damage to buildings in San Francisco de Sales. Five houses were burned by incandescent ballistic blocks; if it had not been raining at the time the fire damage throughout the town would have undoubtedly been much worse. Approximately 90% of roofs in the town were badly damaged, primarily by ballistic impacts, and needed to be replaced.

- After the eruption, there were ten days of power outages in the area around the volcano. This was primarily due to ballistic damage to lines and poles, and also tree fall onto lines. Some 90% of lines in San Francisco de Sales, El Cedro and Calderas were damaged.
- San Francisco de Sales also lost its water supply for eight days as pipework suffered extensive damage from ballistic clasts.
- The access road into San Francisco de Sales and Calderas was impassable except by 4WD, until the tephra compacted into a new surface.

Emergency response

- INSIVUMEH and CONRED have built a working relationship that relies on trust and communication flow, which worked well during the last eruption.
- The emergency management system is improving with time and experience, although information flow from local to national level is not yet fluid and responsibilities at each level require further definition.
- The communities with previous experience of eruption impacts and tephra falls are aware of the risks posed by the volcano and respond to evacuations or tephra falls with less panic than in previous events.
- Available civil defence data suggested that the impact of Tropical Storm Agatha was much greater and more widespread than the impact of the eruption of Pacaya volcano.
- Emergency response was slow in the proximal village of San Francisco de Sales; with no cleanup help from the municipality and delays in deploying medical teams.

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We thank Professor David Johnston of the Joint Centre for Disaster Research, Massey University Wellington and GNS Science, and Dr Tiziana Rossetto, of University College London, for supporting this work intellectually, logistically and financially.

We also particularly thank Professor Bill Rose, and Rudiger Escobar Wolf, both of Michigan Technological University, for generously sharing information with us on their investigations into the recent eruptive history of Pacaya and the 27 May 2010 eruption.

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Finally, we thank our reviewers Jim Cole of the University of Canterbury and Sara McBride of GNS Science for their help in improving the quality of this report and extend further thanks to Rudiger Escobar Wolf for his informal review comments.

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APPENDICES

Appendix 1	Trip itinerary
Appendix 2	Data collection inventory
Appendix 3	Analysis of Pacaya volcano tephra from 27 May 2010 eruption
Appendix 4	Ethics approval numbers
Appendix 5	Report on admissions to the adult emergency department of Hospital x, due specifically to the Pacaya volcanic eruption or tropical storm Agatha
Appendix 6	Analysis of ash from Pacaya volcano for the assessment of health hazard

APPENDIX 1 TRIP ITINERARY

Institution Visited	City Location	Date
ORMAT Geothermal Plant	San Francisco de Sales	19.09.10
Empresa Municipal de Agua (Guatemala) (EMPAGUA)	Guatemala City	20.09.10
Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia (INSIVUMEH)	Guatemala City	20.09.10
Ministerio de Salud Publica (Ministry of Public Health)	Guatemala City	21.09.10
Empresa Electrica de Guatemala (EEGSA)	Guatemala City	21.09.10
Mapreco Waste Services	Guatemala City	22.09.10
Coordinadora Nacional para la Reducción de Desastres (CONRED)	Guatemala City	22.09.10
Hospital A [public]	Guatemala City	23.09.10
Instituto Nacional de Electrificacion (INDE), Empressa de Transporte y Control de Energia Electrica (ETCEE)	Guatemala City	23.09.10
Municipality	Guatemala City	23.09.10
Hospital B [public]	Guatemala City	24.09.10
Basurero	Guatemala City	24.09.10

APPENDIX 2 DATA INVENTORY: RESOURCES GATHERED DURING FIELDWORK

<table>
<tr><th>Donated By</th><th>Type of Resource</th><th>Details</th></tr>
<tr><td rowspan="6">Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia (INSIVUMEH)</td><td>Photos</td><td>Photos of May 2010 activity and of tephra impacts on nearby communities</td></tr>
<tr><td>Report</td><td>Preliminary eruption of Pacaya volcano on 27 May, 2010</td></tr>
<tr><td>Presentation</td><td>Overview of the impacts from May 2010 eruption of Pacaya volcano (in English)</td></tr>
<tr><td>Report</td><td>Overview of the impacts from May 2010 eruption of Pacaya volcano(in Spanish)</td></tr>
<tr><td>Report</td><td>Eruption of Volcán Santiaguito, April 2010</td></tr>
<tr><td>Data</td><td>Real-time seismic amplitude measurements (RSAM) for Volcán de Pacaya during May 26-June 1, 2010</td></tr>
<tr><td rowspan="2">Empresa Electrica de Guatemala (EEGSA)</td><td>Photos</td><td>Photos of EEGSA substations contaminated in Volcanic tephra.</td></tr>
<tr><td>Data</td><td>EEGSA system faults logged between 27 May - May 30, 2010. Many of these faults are attributed to tephra contamination.</td></tr>
<tr><td>Mapreco Waste Services</td><td>Photos</td><td>Photos of tephra cleaning at major waste water facilities.</td></tr>
<tr><td>Municipality</td><td>Presentation</td><td>Overview of eruption, impacts from tephra fall and restoration efforts.</td></tr>
<tr><td>Hospital B [public]</td><td>Photos</td><td>Photos of tephra cleaning.</td></tr>
</table>

APPENDIX 3 ANALYSIS OF PACAYA TEPHRA FROM 27 MAY 2010 ERUPTION

This information was supplied by Alvaro Zepeda, the General Manager of Mapreco. It has been translated from Spanish. The analysis was commissioned by a company who were interested in the re-use potential of the tephra as aggregate for concrete production.

Chemical analysis

SiO_2	49.1%
Fe_2O_3	14.3%
Al_2O_3	18.48%
CaO	8.85%
MgO	3.65%
K_2O	0.82%
Na_2O	2.79%

Physical analysis

Mean grain size: 2.01 Φ

Tephra had a highly heterogeneous grain size distribution.

Relative density: 2.45 g/cm^3

% Absorption: 2.22

Organic matter: 0 colour

Compacted unit weight: 1053 kg/m^3

Loose unit weight: 944 kg/m^3

Wet loose unit weight: 747 kg/m^3

The concrete company concluded that the tephra was unsuitable for use as aggregate, because it was heterogeneous with respect to grain size, and also that its reactivity made it potentially harmful in concrete production. No information on leachate chemistry was obtained.

APPENDIX 4 ETHICS APPROVAL NUMBERS

University College London - 2327/001

University of Canterbury - 2010/118

APPENDIX 5 REPORT ON ADMISSIONS TO THE ADULT EMERGENCY DEPARTMENT OF HOSPITAL A, DUE SPECIFICALLY TO THE PACAYA VOLCANIC ERUPTION OR TROPICAL STORM AGATHA

28-30 May 2010							
No.	AGE	SEX	ORIGIN	DIAGNOSIS	DATE	STATE[1]	EMERGENCY TYPE[2]
1	13	M	5ta. Ave. 1-46, zona 12, Guajitos	Fracture, left arm	28/05/2010	V	V
2	56	M	Prados de Villa Hermosa	PTM, second degree burns	28/05/2010	V	V
3	17	M	12 Calle 18-82, zona 12	TCE exposure	28/05/2010	V	V
4	15	F	Zona 7	Multiple injuries, post-traumatic back pain	28/05/2010	V	V
5	29	M	Avenida Petapa, 53 calle , zona 12	Traumatic brain injury	28/05/2010	M	V
6	18	F	Calzada Justo Rufino, Barrios, Zona 21	Dislocated elbow	28/05/2010	V	V
7	40	F	Villa Nueva, zona 7	Multiple trauma	28/05/2010	V	V
8	48	M	Ciudad Quetzal	fractured wrist	28/05/2010	V	V
9	38	M	Zona 7	Fracture of left foot	28/05/2010	V	V
10	47	F	Zona 11	Multiple trauma	28/05/2010	V	V
11	58	M	Zona 19	Multiple trauma	28/05/2010	V	V
12	48	M	Villa Nueva	Hip contusion	28/05/2010	V	V
13	14	M	Zona 19	Multiple serious injuries, bruised eye (?)	28/05/2010	V	V
14	16	M	Zona 12	Bruised forehead + ??	28/05/2010	V	V
15	35	M	Zona 7	Dislocated left shoulder and finger	28/05/2010	V	V

16	24	F	Zona 19	Dislocated elbow, fractured radius	28/05/2010	**V**	**V**
17	64	F		Traumatic brain injury	28/05/2010	**M**	**V**
18	57	M	Zona 21	Herida Cortocontundente en MII	28/05/2010	**V**	**V**
19	72	M	San Miguel Petapa	Fracture of right foot	28/05/2010	**V**	**V**
20	57	F	Villa Nueva	Fractured fibula	28/05/2010	**V**	**V**
21	26	M		Injury to chest and back	28/05/2010	**V**	**V**
22	14	M		Bruises	28/05/2010	**V**	**V**
23	52	M	Ciudad Quetzal	Electrical burns and fractured pelvis	28/05/2010	**V**	**V**
24	33	M	Zona 11	Multiple trauma	28/05/2010	**V**	**V**
25		M		'Herida Cortocontundente'	28/05/2010	**V**	**V**
26		M		Multiple trauma, head trauma Grade 1	28/05/2010	**V**	**V**
27	32	M	Zona 12	Fracture of left leg	28/05/2010	**V**	**V**
28	16	F	Zona 6	Bronchial hyper-reactivity	28/05/2010	**V**	**V**
29	65	M	Zona 6	Bronchial hyper-reactivity	28/05/2010	**V**	**V**
30	47	M	Zona 12	Allergic reaction	28/05/2010	**V**	**V**
31		M		Multiple trauma	28/05/2010	**V**	**V**
32	22	M	Zona 7	Multiple trauma	28/05/2010	**V**	**V**
33		M		Multiple trauma	28/05/2010	**V**	**V**
34	32	M		Dislocated shoulder	28/05/2010	**V**	**V**

35	20	M		Bruises	28/05/2010	**V**	**V**
36	23	M	Boca del Monte, Villa Canales	Fracture of knee, tibia (?)	29/05/2010	**V-A**	**V**
37	36	M	22 Ave. 16-60, zona 10, colonia Concepción	Hip fracture	29/05/2010	**V**	**V**
38	39	F	San Pedro Sacatepéquez	Grade III fracture	29/05/2010	**V**	**A**
39	74	F	Colonia 1ro. De Julio	Hip fracture	29/05/2010	**V**	**V**
40	67	F	5a. Ave. 3-72, zona 8 de Mixco, San Cristóbal	Fractured tibia	29/05/2010	**V**	**V**
41		M		burns from high tension power lines	29/05/2010	**V**	**A**
42	34	F	Kilómetro 16,5 Carretera a el Salvador	Fracture of left shoulder in a fall	29/05/2010	**V**	**V**
43	30	F	Zona 1 de Boca del Monte, Villa Canales	L1 fracture, compound (?)	30/05/2010	**V**	**V**
44	47	F	Villa Canales	Distal radius fracture	30/05/2010	**V**	**V**
45	18	M	Zona 7	Fracture of tibial plateau	30/05/2010	**V**	**V**
46	36	M	Zona 10	Dislocated finger, acetabular fracture	30/05/2010	**V**	**V**
47	40	M	San Miguel Petapa	Displaced skull fracture	30/05/2010	**V**	**V**
48	48	M		Fracture of distal radius	30/05/2010	**V**	**V**
49	50	M	Villa Canales	L1 fracture, compound (?)	30/05/2010	**V**	**V**
50	35	M	12 calle B, 20-69, zona 11	Fracture of tibia at MII	30/05/2010	**V**	**V**
51	14	M	Villa Canales	Hand fracture	30/05/2010	**V**	**V**
52	55	F	Zona 19	Left lower limb fracture	30/05/2010	**V**	**V**
31 May onwards							

No.	AGE	SEX	ORIGIN	DIAGNOSIS	DATE	STATE	EMERGENCY TYPE
1	33	M	Los Próceres, Zona 10	Multiple trauma and head trauma from falling from roof	31/05/2010	V	V
2	18	M	6a. Ave. 4-20, zona 1, El Porvenir, Villa Canales	Multiple trauma, a fall from roof	31/05/2010	V	V
3	59	M	Nueva Monserrat, zona 3 de Mixco	Multiple trauma, head injury and wrist fracture from falling	31/05/2010	V	V
4	15	M	Colonia los Alamos, zona 6, San Miugel Petapa	Multiple trauma caused by fall	31/05/2010	V	V
5	37	M	Calle C 4-4, colonia Seis de Octubre, Guatemala	Multiple trauma caused by fall	31/05/2010	V	V
6	50	F	Colonia primero de Julio	Sprained right ankle caused by fall	1/06/2010	V	V
7	24	F	Villa Canales	Scaphoid fracture - fall	1/06/2010	V	V
8	50	F	San Miguel Petapa	Distal radius fracture, falling from roof	1/06/2010	V	V
9	40	M	Obelisco, viaducto entre zona 9 y zona 10, ciudad Guatemala	Poisonous gas inhalation and contaminated water while carrying out underground work for municipality	1/06/2010	V	A
10	43	M	Obelisco, viaducto entre zona 9 y zona 10, ciudad Guatemala	Poisonous gas inhalation and contaminated water while carrying out underground work for municipality (rescued from well)	1/06/2010	V	A
11	32	M	5a. Avenida y 5ta. Calle, zona 9, ciudad Guatemala	Multiple trauma, a fall from roof	1/06/2010	V	V
12	13	M	Trasladado del Hospital Nacional de Antigua Guatemala	Multiple trauma caused by fall while cleaning tephra from gutter	1/06/2010	V	V
13	25	M	Avenida la Castellana y 40 calle, zona 9, Ciudad	Multiple trauma from traffic accident, slid on tephra	1/06/2010	V	V
14	24	M	Avenida la Castellana y 40 calle, zona 9, Ciudad	Multiple trauma from traffic accident, slid on tephra	1/06/2010	V	V
15	44	F	Zona 7 de San Miguel Petapa	Multiple injuries falling from roof	2/06/2010	V	V
16	27	F	Zona 8 de Mixco, Guatemala	Multiple injuries falling from roof	2/06/2010	V	V

17	12	M	zona 9, de San Miguel Petapa	Multiple injuries falling from roof	2/06/2010	V	V
18	17	M	Villa Canales, Guatemala	Multiple injuries falling from roof	2/06/2010	V	V
19	16	M	Villa Lobos, I, zona 12	Multiple injuries from fall	03/062010	V	V
20	19	F	villa Nueva	Asthmatic crisis	3/06/2010	V	A
21	49	M	San Miguel Petapa, Guatemala	Multiple injuries from fall	7/06/2010	V	V
22	18	M	Boca del Monte, Villa Canales, Guatemala	Pharyngitis from breathing tephra	7/06/2010	V	V

1 V = vivo (alive); M = muerto (dead)
2 V = volcanic crisis; A = Agatha (tropical storm)

APPENDIX 6 ANALYSIS OF ASH FROM PACAYA VOLCANO FOR THE ASSESSMENT OF HEALTH HAZARD

Claire J. Horwell and David E. Damby

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19 January 2011

Introduction

Two ash samples from the eruption of Pacaya volcano were sent to Durham University (UK) by Dr Bill Rose on 27 May 2010. We have carried out basic analyses to test for potential health hazard. Sample information is as follows:

Table 1

Sample #	Grid location	Distance from Pacaya	Bearing	Info	Collector
PAC2010_01	14°35'32.34"N 90°29'8.82"W	26.7 km	208°	Part of a 3 mm thick layer, collected dry, unaffected by rain	Samuel Bonis
PAC2010_02	15°28'14.80"N 90°22'20.09"W	122 km	192°	Wet but not soaked	

Methods

The following analyses were carried out:

1. Grain size distributions by laser diffraction using a Malvern Mastersizer 2000 with Hydro Mu.
2. Major element analysis (bulk composition) using X-Ray fluorescence.
3. Crystalline silica quantification (cristobalite and quartz) using X-ray diffraction with static position-sensitive detection (XRD-sPSD).

Results

Bulk composition analyses confirmed that the ash samples are basaltic (51.6 and 50.8 wt. % SiO_2; 3.9 and 4.8 wt. % Na_2O and K_2O).

Grain size analyses showed that there is no respirable or inhalable ash in either sample (Table 2). It is possible that some minor fines component had been lost from PAC2010_02 given that the 63 µm contained 7.89 vol. % material (which would give a predicted value of ~0.44 vol. % <4 µm and ~1.9 vol.% <10 µm material according to Horwell (2007).

Table 2 Quantity of material in health-pertinent size fractions in vol.%.

Bin	Fraction	PAC2010_01	PAC2010_02
<1 µm	Ultrafine	0.00	0.00
<2.5 µm	“	0.00	0.00
<4 µm	Respirable	0.00	0.00
<10 µm	Thoracic	0.00	0.00
<15 µm	Inhalable	0.00	0.00
<63 µm	Sievable	0.00	7.89

There was negligible crystalline silica in the samples, although PAC2010_02 has 3.41 wt%, indicating that there are small quantities of cristobalite in the ash.

Table 3 Amount of crystalline silica in the samples, 1-3 wt.% error

Sample #	Cristobalite wt%	Quartz wt%
PAC2010_01	0.00	0.79
PAC2010_02	3.41	0.00

Discussion

From a health perspective, this basaltic ash is not likely to cause significant respiratory issues. Neither sample contained any material that could penetrate into the respiratory system. In addition, as expected for a basaltic eruption, crystalline silica content was negligible. The small amount of cristobalite observed may have been sourced from altered edifice rock entrained into the eruption column. There is the possibility that the ash could be reactive in the lung due to iron-catalysed hydroxyl radical generation, as observed for ash from previous eruptions of Pacaya and other basaltic volcanoes. However, as the ash is not inhalable, we did not carry out these experiments.

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